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https://doi.org/10.1021/acs.joc.7b03063

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Indium- and Zinc-Mediated Acyloxyallylation of Protected and Unprotected Aldotetroses—Revealing a Pronounced Diastereodivergence and a Fundamental Difference in the Performance of the Mediating Metal

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ABSTRACT: The acyloxyallylation of unprotected aldoses was first demonstrated more than a decade ago as a potentially elegant two-carbon homologation of reducing sugars (upon ozonolysis); however, its application in real case syntheses remained scarce. Following up on such a successful showcase and to answer several pending questions about this attractive transformation, we engaged in an in depth methodological reinvestigation. The epimeric tetroses L-erythrose and D-threose in unprotected and protected form were successfully applied to the indium and also zinc-mediated acyloxyallylation, with the latter being a first for an unprotected sugar. The investigation largely benefited from the choice of these more exotic starting materials as it allowed unambiguous identification/quantiﬁcation of the hexose-products which are available as authentic reference materials. The observed diastereoselectivities indicate a strong substrate control (stereochemistry at O2), and the inﬂuence of the reagent’s structure on the selectivity was investigated in great detail. A strong facial diastereodivergence between related protected and unprotected structures was demonstrated and an unexpected, pronounced principle diﬀerence in performance between indium and zinc was revealed.

INTRODUCTION

Carbohydrates are regularly referred to as an important part of Nature’s chiral pool. However, commercial or facile availability at desirably low cost or effort is in fact limited to only selected representatives of this substance family,1,2 resulting in two undesirable consequences: First, the use of carbohydrates as chiral starting materials remains often limited to a subset of “common” sugars, and second, methodology development is usually only demonstrated on this same set of abundant derivatives, creating a reinforcing cycle: The use of more exotic sugar building blocks is discouraged by the lack of positive literature precedence. Approaches to extend the range of sugars are being targeted by biotechnology3 as well as efforts in the field of de novo syntheses;4−6 however, the challenge of mastering the stereoselective modiﬁcation of one or more centers of an otherwise readily available chiral scaffold is certainly an attractive complementary endeavor. Our current report outlines the potential value of including currently less abundant sugars into a methodological study and in parallel serves our ultimate motivation to increasing the platform of readily available parent sugars for the carbohydrate community and beyond.

In this context, the indium-mediated acyloxyallylation (IMA) of unprotected aldoses with halopropenyl esters as reactants presents great potential as an elegant two-carbon homologation of reducing sugars (upon facile loss of ester protection and subsequent ozonolysis). The use of IMA is a particularly practical approach as the indium (and analogous zinc) organometallics can be formed and reacted under Barbier-type-conditions. Of note the observed selectivities have been shown to be independent of the (E/Z)-conﬁguration of the reagents and a wide range of reaction conditions are tolerated including protic solvents (alcohols, aqueous solutions) and ambient temperatures.7−10 In an initial proof of concept study, standard D-pentoses and D-hexoses were studied as starting materials and the formation of only two out of four

Received: December 4, 2017
Published: January 25, 2018
possible isomers was reported, with moderate to good selectivity for the main product. Only the main products were isolated and identified which exhibited consistently the same relative stereochemistry, namely a lyxo-configuration. This configuration represents an anti-orientation of the two new stereocenters formed, in a syn-fashion with respect to the α-position of the carbonyl moiety in the starting material (Figure 1, top). While the anti-addition was in line with the established model for the acyloxyallylations of achiral aldehydes, the facial selectivity (syn) in respect to the addition to the carbonyl seems specific to sugars as starting materials. The other isomers were not isolated or identified. Therefore, although widely acknowledged in the literature, this chemistry was never fully explored or exploited.

Recently, we developed a large-scale concise synthesis of the important bacterial sugar L-glycero-D-manno heptose 2 starting from L-lyxose, featuring a practical preparative indium-mediated acyloxyallylation protocol toward the highly crystalline manno-configured enitol 1a (lyxo-type addition) as the key synthetic step. En route, we additionally isolated two further isomers which were identified as the gluco- and allo-configuration (1b, 1c), derived from xylo- and ribo-type addition, respectively (Figure 1, middle). In contrast to the original paper (D-lyxose) we observed a significantly less pronounced selectivity for the main isomer and also less of an enhancement when replacing bromopropenyl acetate (1a/1b/1c = 65:25:10) with the corresponding benzoate (1a/1b/1c = 70:20:10). Success in this case study was ultimately derived from the beneficial physical properties of enitol 1a in its downstream processing. The observed ratios imply a high facial selectivity for the attack of the indium organyl from the si-face of the carbonyl (90% for the two main products), with a moderate anti-selectivity (1a/1b ~ 2:1 up to 3.5:1) in the addition step (see Figure 2 for the separate consideration of the two types of selectivity). To the best of our knowledge, this constitutes the first complete set of data describing the outcome of an indium-mediated acyloxyallylation in a complex setting that employing sugars as starting materials constitute. Building upon the knowledge generated, we have decided to expand our efforts into a methodological study to address several open questions in this attractive transformation.

### Setting up our methodological survey.
To cope with the inherent difficulty of structural analysis of unknown carbohydrate structures as well as the reliable quantification of (isomeric) mixtures thereof, we chose the tetroses L-erythrose and D-threose as substrates for our survey. These species represent two different relative stereochemical configurations (erythro, threo) next to the reactive carbonyl center, and with hexoses being the final elongation products (upon ozonolysis), unambiguous identification of all potential products can be guaranteed by comparison with authentic reference materials.

The first question we wished to investigate was whether the product distribution, revealed in our case study, was general and if the moderate selectivity in the addition step could be improved upon via optimization of the reagent. Furthermore, according to the reported literature as well as our own experience, replacement of indium with cheaper zinc was unsuccessful in the acyloxyallylation of aldoses while it gave comparable results with standard aldehydes, a result not explained so far. Thus, we set out to better understand the particular challenge of employing zinc in the case of carbohydrate starting materials (Figure 1, bottom right). We also decided to evaluate the corresponding 2O,3O-isopropylidene protected derivatives in our survey, expecting to observe facial diastereodivergence, yielding the anti/anti-products (ribo-type addition) (Figure 1, bottom left). Precedence for such an inversion of selectivity can be found for example with Garner’s aldehyde, one of the few transformations of chiral starting materials with bromopropenyl acetate.

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**Figure 1.** Progress of the state of knowledge of the indium- (and zinc-) mediated acyloxyallylation of aldoses. Reagent (blue) and sugar-derived (red) new stereocenters and partial structures are color-coded.
esters. A related facial diastereodivergence was also reported in the simple alkylation (only one new stereocenter) of protected and unprotected sugar derivatives, and the 1,2-addition of 3-bromomethyl-3H-furan-2-one to α-chiral aldehydes under the mediation of indium. When L-erythrose was subjected to the standard reaction conditions as applied in our previous case study, both with respect to the newly formed stereocenters (Figure 2).

For the sake of clarity, the overall process of the addition is hypothetically separated into the approach of the indium organyl to the aldehyde, and the actual addition step to the carbonyl, related to the simple diastereoselectivity in the formation of the two new stereocenters (Figure 2).

RESULTS AND DISCUSSION

Acetyloxyallylation of protected and unprotected L-erythrose. We started our investigation with the erythrose series. We first synthesized L-erythrose (available but at high prices) from cheap L-arabinose by 3O/4O-isopropylidene protection (4), oxidative cleavage with NaIO₄ (5), and subsequent acidic hydrolysis to furnish 6. It is noteworthy that a high degree of the open chain form is present in solutions of 6 (~10% as hydrate according to 1H NMR in D₂O), which is of importance in the later discussion. Alternative treatment of 4 with silica supported NaIO₄ under nonaqueous conditions furnished protected L-erythrose sugar aldehyde 7 species, a more reactive version of 5 (Scheme 1).

When L-erythrose 6 and bromopropenyl acetate 3a were subjected to the standard reaction conditions as applied in our preliminary case study (EtOH, indium, 45 °C, 10 min), rapid and full conversion was observed, delivering a mixture of three isomeric enitols (8a/8b/8c = 66:18:14) upon decacylation. The two major isomers (8a, 8b) were obtained in pure form via their peracetates (9a, 9b) and were subjected to a modern ozonolysis protocol adopted by us for polar compounds toward the corresponding sugars L-mannose 10 and L-glucose 11 (Scheme 2, middle). Their structures were unambiguously proven by comparison (1H, 13C NMR) to authentic samples (D-hexoses), thus confirming the expected additions (lyxo, xylo) as predicted from our case study. The stereochemistry of the third compound 8c was elucidated to be the allo-anti, upon isolation from the analogous experiments with sugar aldehyde 7, in which 8c was formed as the major isomer accompanied by the altro-isomer 8d (8c/8d = 84:12). Ozonolysis of the crude allo-enitol (8c/8d) allowed the isolation of pure L-allose 12 achieved by recrystallization and identification of both sugars (L-altrose 13 in mother liquor) again by comparison with authentic samples (Scheme 2, bottom). All attempts to achieve analogous conversion of 5 (as a simpler version of 7) under several conditions in different solvents remained unsuccessful, which is attributed to the high stability of the bicyclic system in lactol 5 resulting in low formation of the required open chain form. Quantification of isomers 8a–d was consistently performed either by 1H NMR (diagnostic allylic signals of processed mixtures) or more conveniently by GC-analysis of crude mixtures upon per-OTMS silylation.

In summary a high degree of facial diastereodivergence was observed with 6 and 7, respectively. While the facial (carbonyl) selectivity was high (85~95%) in both cases, the diasteroselectivity in the addition step was high (7:1) in the protected case (7) but only moderate for the acyloxyallylation of the unprotected L-erythrose (5). The ratio found (8a/8b/8c = 66:18:14) in the latter case is in line with the results of our previous case study, both with respect to the newly formed stereochemical constitution in the products (lyxo, xylo, ribo) as well as the ratios between them.

The facial selectivity for the si-face in the case of the unprotected sugars can be rationalized by a Cram-chelate model...
while a Cram-type model (with the O2-oxygen in the anti-periplanar position to the carbonyl) predicts the diastereoselectivity for the protected case (Figure 3, bottom). The anti-selectivity in the addition step to the carbonyl is in line with the mechanistic model established for the acyloxyallylation of achiral aliphatic aldehydes by Lombardo and Trombini (vide infra).9

Acetyloxyallylation of protected and unprotected D-threose. Next, D-threose 14 (the 3-epimer of L-erythrose) and the related protected sugar aldehyde 15 were subjected to the same reaction conditions as indicated above (3a, In, EtOH, 45 °C). Compound 15 was prepared via a literature approach24 with necessary modification of the final oxidation step.25 Clean and full conversion was again achieved for both starting materials, and the crude reactions mixtures were processed to their fully unprotected enitols 16a−d for quantification as described above (Scheme 3, top).

A very pronounced facial diastereodivergence between the conversion of unprotected (14) and protected D-threose 15 with a high degree of facial diasteroselectivity (>90%) was observed. In addition the simple diastereoselectivities were consistent with the erythro-case, in terms of both the types of addition products as well as their ratios (14: lyxo > xylo > ribo; 15: ribo > arabino).26 A comparably lower selectivity was observed in the conversion of 15 (∼7:2 anti:syn in the threo-case versus ∼7:1 in the erythro-case); it is noteworthy that due to different synthetic routes, O4-acetate protection was in place in 15 in contrast to the O4-formate in 7.

Purified diasteromers 16a−d were obtained via chromatographic separation of the corresponding peracetates 17a−d or by direct crystallization as in the separation of the talo- and galacto-configured enitols 17c/17d. The stereochemical constitution was again proven by conversion to the reducing sugars (18−21) and comparison (1H and 13C NMR) to authentic commercial samples.

To facilitate the comparison of the results of the erythro- and threo-series, the corresponding product distributions are summarized in Figure 4, with reference to the stereochemical-type of addition rather than the actually formed structures.
Optimization of the reagent to improve simple diastereoselectivity. Prompted by the moderate selectivities in the conversion of the unprotected tetroses (6, 14), we decided to systematically investigate if the steric bulk of the ester moiety in the reagent can positively modulate the simple diastereoselectivity observed. Our hypothesis was based on the mechanistic

Figure 4. Summary of product-distributions in the acyloxalylations of protected and unprotected tetroses (6, 7, 14, 15). The formed products are referred to by the newly established relative stereochemistry (xylo, lyxo, ribo, arabino) to allow for comparison between the two series.
model established for simple achiral aldehydes by Lombardo and Trombini that aldoses apparently follow as well (Figure 5). The model rationalized the observed anti-selectivity with saturated aldehydes (and the stereocrosser with unsaturated aldehydes exhibiting syn-selectivity)\(^9\) with a boat-like conformation in the relevant transition states (TS) which was further supported by an extensive computational study.\(^26\) The boat-like conformation allows an additional positive stabilization of the metal center by the ester moiety (as in the \(\gamma-Z\)-form of the parent indium organyl) which is not in place in the alternative classical Zimmerman–Traxler model. The TS leading to syn or anti-addition products according to the suggested model (top) and the alternative classical Zimmerman–Traxler model, predicting generally syn-addition, are depicted for the erythro-products 6 and 7 in Figure 5. Instead of showing an enantiomeric TS for 7, enantiomeric ent-7 is depicted to correctly represent the formation of the two different major anti-products.

According to the Lombardo–Trombini-model, the formation of an anti-isomer should be independent of the size of the ester moiety (TS-A) while the transition states leading to the syn-isomer (TS-B) would be affected by the steric congestion between the residue (sugar chain) and the ester group. Therefore, increasing bulk in the reactant would be expected to favor formation of the preferred anti-isomer (i.e., 8a, 8c).

To test this hypothesis, we synthesized a series of bromopropenyl esters with different steric demands (isobutyrate 3c, pivalate 3d, benzoate 3b, 1-naphthoate 3e, and mesitoate 3f)\(^27\) and utilized them in the acyloxyallylation of \(l\)-erythrose 6. Iodopropenyl pivalate 22 (via the corresponding chloride 23\(^28\)) was included in the survey as a particularly reactive species to assist the replacement of indium by zinc as the mediating metal. It is noteworthy that, in all transformations of 3a–f with indium, a full and clean conversion of 6 was achieved. Upon deacylation and subsequent GC-analysis, a stepwise increase of the simple diastereoselectivity (8a/8b-ratio) was observed (3a < 3c < 3d, 3b) (see Figure 6, lines 1–4). The application of the corresponding naphthoate 3e did not give a significant additional increase in selectivity compared to benzoate 3b (line 4–5) and an attempted investigation of mesitoate 3f\(^29\) (structure not shown) was hindered as, upon successful acyloxyallylation, the ester could not be cleaved to allow isomer-analysis. Of note the difference in selectivity between 3a and 3d is significantly more pronounced compared to our case study with \(l\)-lyxose, a pentose with the same stereochemistry at O2/O3 compared to 6.\(^14\)

**Realization of the zinc-mediated acyloxyallylation of an unprotected sugar.** The reaction of iodide 22 gave comparable product ratios to the standard bromide 3d as mediated by indium; in addition it also showed complete product formation when reacted with zinc dust. This is in strong contrast to all earlier reports including our own experience with \(l\)-lyxose which failed to give any measurable conversion. To our best knowledge, this constitutes the first successful zinc-mediated acyloxyallylation of an unprotected aldose. However, closer analysis of the enitol product distribution revealed an entirely different picture compared to the use of indium. The observed product ratios (8a/8b/8c/8d = 38:9:40) indicated that the facial selectivity was completely lost while the simple diastereoselectivity remained in a similar range. The loss of facial selectivity under mediation of zinc was conﬁrmed with other reagents (3a shown), revealing a striking difference in principle performance between indium and zinc in the acyloxyallylation of a chiral chelating starting material such as \(l\)-erythrose (Figure 6, lines 6–8). In contrast, the analogous experiment with acetonide 7, 3a, and zinc showed no detrimental effect on the facial-selectivity, providing comparable values to the alternative indium mediation (Figure 6, lines 9–10). For the latter case the study with chiral Garner’s aldohexane can be considered a precedence.

**Mechanistic considerations for the zinc-mediated acyloxyallylation.** Although the lost facial selectivity with zinc as mediator renders the replacement of indium synthetically irrelevant, it enables some interesting deductions to be elicited. The striking difference between the indium and zinc organyls supports an interpretation that the facial syn-selectivity observed in the unprotected case with indium (but not zinc) results from a chelating effect of the incoming organyl. The alternative explanation within the framework of a Cram-model would require the sugar chain of 5 to adopt an antiperiplanar orientation to the carbonyl (instead of the O2 with 7, Figure 3), but this would not explain the complete loss of facial selectivity when zinc is used. Nonetheless, the sole reactivity of \(l\)-erythrose 6 under zinc-mediated reaction is quite remarkable, and we hypothesize this originates from the exceptionally high proportion of the open chain form in tetroses (~10%) which would single them out from all other longer-chain parent aldoses. The high concentration of available aldehyde species (and more
importantly, the fast re-equilibration to form this species) allows the acyloxyallylation under the mediation of zinc to take place rapidly. With the usual pentoses/hexoses, the (re)formation of the open chain structure from the dominant cyclic hemiacetal is apparently too slow to compete with reagent side reactions (e.g., Wurtz-type dimerization, alcoholysis).

Elucidation of the fate of halopropenylesters in alcoholic solutions. Only a short reaction time is required for complete and clean conversion in all indium-mediated acyloxyallylations with unprotected sugars, but an excess of reagent/indium is required and, importantly, sufficient stirring.30 The fast formation of Wurtz-type byproducts in water has been reported9 as a potential sink of reagent 3a, which could not be confirmed by us in EtOH in blank experiments; only small amounts of material (potential Wurtz-type products) were recovered, with volatiles being the major side-products. In order to increase the understanding of the fate of the bromopropenyl esters under the protic conditions required to solubilize unprotected sugars, we dissolved 3a in MeOH-d4 and observed its rapid alcoholysis (to 25-d4) and slower conversion to the 26-d10 (deuterated version of 1,1,3-trimethoxy propane 26) over time (1H NMR). The formation of 26-d10 was supported by analogous reactions in MeOH and EtOH at preparative scale and comparison of isolates to commercial 26 and 27 (Scheme 4 and Supporting Information).

From this investigation we conclude that rapid alcoholysis consumes the reagent in competition with the formation of the indium organyl and in doing so liberates HBr which is responsible for the observed drop in pH and likely also for the formation of ethyl glycosides, observed in the case of incomplete initial conversion.13,14 Under ideal reaction conditions, the formation of the indium organyl is fast enough to give a clean conversion even with standard reducing sugars (low content of open chain form). As indicated by the full conversion of 6, the analogous zinc organyls can apparently be formed under the same reaction conditions, but more readily available aldehyde species are required to achieve acyloxyallylation (in time). This prerequisite is fulfilled in the case of L-erythrose but not with the other tested aldoses. Whether, under the indium mediation, the chelation with O2 is not only responsible for the high degree of facial selectivity but also activates the reducing sugar toward the reaction cannot currently be answered.

■ CONCLUSION

With a coherent set of molecular probes (tetroses) we have undertaken an in-depth investigation of the indium and zinc-mediated acyloxyallylation of protected and unprotected tetrose structures. It has been shown that, independent of the relative stereochemistry at C2/C3, consistent product distributions (also to the one described by us earlier for L-lyxose) can be attained. A generally high facial selectivity is exhibited, outlining a strong substrate control with respect to the stereochemistry in the α-position to the reactive carbonyl. Furthermore, a pronounced...
diastereodivergence was observed depending on whether or not O2/O3-isopropylidene protection was in place. Increasing bulk in the ester group promotes the selectivity for the β-xylo-type addition to L-erythrose, an observation which is consistent with the model established for achiral aldehydes. With unprotected L-erythrose, we accomplished for the first time the replacement of indium by zinc as the acyloxyallylation mediator; however, the high facial selectivity observed with indium was entirely lost, a striking difference between the two metals which can only be observed in this complex setting of a chelating chiral starting material. This observation is a beautiful example of the value of including other more exotic sugars into methodological work. Through a structured and detailed investigation of the indium and zinc-mediated acyloxyallylation of tetroses, several outstanding questions pertaining to this attractive but complex transformation have finally been clarified. This consolidated knowledge allows for more refined predictions, and we hope it will inspire more people to consider acyloxyallylation as a synthetic tool, within and beyond the realm of carbohydrate chemistry. Applications toward further short synthetic routes to currently rare and exotic sugars based on acyloxyallylation are currently being developed in our lab.

### EXPERIMENTAL SECTION

**General Methods.** All starting materials and reagents as well as the reference materials for β-hexoses (Carbosynth, UK) were purchased from commercial sources and used without further purification. Dowex 50WX2 hydrogen form was used as an acidic ion-exchange resin. Reactions were monitored by TLC on silica gel 60 F254 plates; spots were detected by UV light examination or visualized by spraying with anisaldehyde–sulfuric acid and heating. Normal-phase column chromatography was performed on silica gel 60 (230–400 mesh). NMR spectra were recorded at 297 K in the solvent indicated, with 400 and 600 MHz instruments, respectively, employing standard software procedures. Compounds 3e, 7 and 22 reproducibly did not give conclusive HRMS results which was attributed to their labile nature which also prevented purification to the high purity required for elemental analysis.

**Determination of enolit distribution derived from erythro-configured starting materials (GC).** Synthesis of heptenitoles 8a-d starting from L-erythrose 6 on analytical scale. L-Erythrose 6 (0.1–0.4 mmol) was dissolved in dry EtOH (0.2 M) and heated to 45 °C. Then, the corresponding halopropenyl ester (3.00 equiv) and indium or zinc (2.00 equiv) were added under vigorous stirring and in immediate succession. After 30 min complete conversion of starting material (staining yellow/green) to a more apolar spot (staining blue) was obtained according to TLC analysis (DCM/MeOH 9:1). The reaction mixture was filtered and solvent and volatiles evaporated. The white residue was taken up in MeOH (0.1 M) and NaOMe was added until a basic pH was reached, which led to the formation of a white precipitate. The reaction mixture was stirred at rt until TLC analysis (DCM/MeOH 9:1) showed complete conversion to a more polar spot when the white precipitate was centrifuged and the supernatant was neutralized with Dowex-H+. The resin was filtered and an aliquot of the filtrate was subjected to GC analysis.

**Synthesis of heptenitoles 8a-d starting from 2/3O-protected erythrose 7.** Dry EtOH (0.1 M) was heated to 45 °C in a round-bottom flask. In immediate succession, first indium or zinc (2.00 equiv), freshly distilled 3-bromoprop-1-en-1-yl acetate 3a (3.00 equiv) and subsequently aldehyde 7 (1.00 equiv, 0.1–0.4 mmol) was added as a solution in little EtOH in one portion. The reaction mixture was stirred at 45 °C for 30 min, when TLC (LP/EtOAc 1:1) showed complete conversion to a more apolar product (staining blue; starting material yellow). The reaction mixture was filtered and the filtrate was evaporated, leaving a white residue, which was acetylated using Ac2O in pyridine, followed by aqueous workup to remove all inorganics. The acetylated product mixture was taken up in dry MeOH and treated with NaOMe until a pH of 9–10 was reached. The mixture was stirred at rt for 1 h, when reaction monitoring via TLC (LP/EtOAc 1:1 and 1:3) showed complete conversion to a more polar spot. The reaction mixture was neutralized by addition of Dowex-H+ resin and filtered. Fresh (MeOH washed) Dowex-H+ was added until a pH < ~2 was determined and the reaction mixture was stirred at rt for 2 h, when reaction monitoring via TLC (DCM/MeOH 9:1) showed complete conversion to fully unprotected heptenitoles 8a–d. The resin was filtered and an aliquot was subjected to GC analysis.

**Persilylation (OTMS) of crude enitols 8a-d and GC-analysis.** An aliquot (containing approximately 0.1–0.2 mg of enitole species) of crude enitol containing solutions was evaporated to dryness. To the dry residue, glycerol (silylation standard) was added in ~ equimolar amounts. The mixture was taken up in a solution of DMAP in pyridine (c(DMAP) 0.75 mg/mL; 400 μL). N,O-Bis(trimethylsilyl)trifluoroacetamide (200 μL, incl. 1% (v/v) TMSCl) was added and the mixture was...
stirred at 70 °C for 4 h. EtOAc (400 μL) was added and after filtration through a syringe filter, the samples were analyzed via GC. The ratio of diastereomers was determined by gas chromatography (GC) using a Thermo Finnigan Focus GC/DSQ II equipped with a standard capillary column (BP5, 30 m x 0.25 mm ID, 0.50 μm film) and a FID detector. carrier gas: helium; injector: 230 °C; column: flow: 2.0 mL/min; oven program: 50–190 °C (50 °C/min) → 190–220 °C (3 °C/min) → 220–310 °C (50 °C/min) → 310 °C (2 min). Retention times: 9.62 (8c), 9.75 (8a), 9.85 (8b), 9.98 (8d) min.

**Determination of enitol distribution derived from three-configured starting materials (1H NMR).** Synthesis of heptenitoles 17a–d (peracetates) starting from 3-threose 14 on analytical scale. 3-Threose 14 (0.5 mmol) was dissolved in dry EtOAc (0.2 M) and heated to 45 °C and bromopropenyl acetate 3a (3.00 equiv) and indium (2.00 equiv) were added under vigorous stirring in immediate succession. After 30 min complete conversion of starting material (staining yellow/green) to a more apolar product (staining blue; starting material yellow). The reaction mixture was stirred and allowed to warm by lowering the cooling bath until −15 °C, when an exothermic reaction caused warming up to +10 °C. The flask was reimmersed in the cooling bath and the temperature was kept under −10 °C for 1 h. A sample (micro workup with EtOAc and sat. NaHCO3 and drying with MgSO4) for analysis via 1H NMR was taken, confirming complete conversion of starting material to the target products. Under cooling H2O (40 mL) was added (temperature rose to −10 °C), which led to the formation of a white precipitate. Layers were separated and the organic layer was washed with H2O (50 mL) and sat. NaHCO3 (until basic pH). The organic layer was washed with brine, dried over MgSO4 and the solvent evaporated, leaving a brown liquid (17.3 g) which was purified by distillation (bp 43 °C, 0.4 mbar) to give pure target compound 3c as colorless liquid (9.00 g, 41%): ratio of E/Z = 1:1.4; (E)-isomer. 1H NMR (400 MHz, CDCl3) δ 7.44 (dt, J = 12.4, 1.1 Hz, 1H, =CH−O−), 5.71 (dt = 12.4, 8.4 Hz, 1H, CH−CH−), 4.00 (dd, J = 8.5, 1.0 Hz, 2H, CH2−Br), 2.63 (hept, J = 7.0 Hz, 1H, CH−CH3), 1.21 (d, J = 7.0 Hz, 6H, 6H, CH−(CH3)x) 13C NMR (101 MHz, CDCl3) δ = 173.7 (s, C=C), 139.5 (d, O−CHx), 111.1 (d, =CH−CHx), 33.8 (d, CH−(CH3)x), 28.8 (t, −CH3−Br), 18.7 (q, −CHx); (Z)-isomer: 1H NMR (400 MHz, CDCl3) δ 7.70 (dt, J = 6.3, 0.8 Hz, 2H, =CH−O−), 5.25 (dd, J = 8.4, 6.3 Hz, 1H, CH−CH=), 4.08 (dd, J = 8.4, 0.8 Hz, 2H, CH2−Br), 2.70 (hept, J = 7.0 Hz, 1H, CH−(CH3)x), 1.25 (d, J = 7.0 Hz, 6H, CH−(CH3)x); 13C NMR (101 MHz, CDCl3) δ = 173.3 (s, C=C), 137.5 (d, O−CHx), 109.5 (d, −CH−CHx), 34.0 (d, −CH−(CH3)x), 23.7 (t, −CH3−Br), 18.8 (q, −CHx);

**3-Bromoprop-1-en-1-yl pivalate (3d)**: Step 1 - synthesis of pivaloyl bromide: PPH3 (26.2 g, 0.1 mol, 1.00 equiv) was dissolved in dry DCM (50 mL) and cooled to −10 °C under an ice-bath. Br2 (15.1 mL, 0.10 mol 1.00 equiv) was added as a solution in dry DCM (50 mL) dropwise, keeping the temperature at 0 °C. PPH3Br2 started to precipitate. After complete addition of Br2 pivalic acid was also dissolved in dry DCM (50 mL) and added quickly to the reaction mixture. The previously formed precipitate got dissolved and stirring was continued at rt for 1 h. Solvent was evaporated and the residue was treated with dry EtOAc, which led to the formation of a lot of precipitate, which was filtered and the solvent was evaporated. The product 3d was obtained by distillation under reduced pressure as a colorless liquid (5.3 g, 32%): bp 25 °C, 10 mbar (lit.34 65 °C at 10 mbar); ratio of Z: E = 1:1.7; (Z)-Isomer 1H NMR (400 MHz, CDCl3) δ = 1.30 (s, 1H, 3 × CH3); 13C NMR (101 MHz, CDCl3) δ = 178.8 (COBr), 52.8 (C(CH3)x), 27.2 (3 × CH3). Step 2: Acrolein (95%, 23.8 mL, 35.7 mmol, 1.00 equiv) for analysis via 1H NMR was taken. This showed complete conversion of starting material to the desired product. H2O (10 mL) was added under cooling (temperature rise to −10 °C). Layers were separated and the organic layer washed with H2O (still acidic) and sat. aq. NaHCO3 (until basic pH). Then, the organic layer was washed with brine, dried over MgSO4 and the solvent evaporated, leaving a brown liquid (9.03 g). The product 3d was obtained by distillation under reduced pressure as a colorless liquid (3.00 g, 42%): bp 38 °C, 0.2 mbar; ratio of E/Z = 1:1.7; (E)-isomer. 1H NMR (400 MHz, CDCl3) δ 7.42 (dt, J = 12.4, 1.0 Hz, 1H, =CH−O−), 5.70 (dt = 12.4, 8.5 Hz, 1H, −CH−CH3), 3.99 (dd, J = 8.5, 1.1 Hz, 2H, CH2−Br), 1.23 (s, 9H, 3 × CH3); 13C NMR (101 MHz, CDCl3) δ 175.2 (C=O), 139.7 (d, O−CHx), 111.1 (d, =CH−CHx), 28.9 (t, −CH3−Br), 27.0 (q, 3 × C(CH3)x); (Z)-Isomer 1H NMR (400 MHz, CDCl3) δ 7.18 (dt, J = 6.2, 0.8 Hz, 1H, =CH−O−), 5.25 (td, J = 8.3, 6.2 Hz, 1H, =CH−CHx), 4.07 (dd, J = 8.4, 0.8 Hz, 2H, CH2−Br), 1.28 (s, 9H, 3 × CH3); 13C NMR (101 MHz, CDCl3) δ 174.7 (C=O), 137.9 (d, O−CHx), 109.6 (d, −CH−CHx), 39.2 (C(CH3)x), 38.9 (C(CH3)x), 27.4 (3 × C(CH3)x), 21.6 (C−CH3−Br), 18.7 (q, −CHx);

**3-Bromoprop-1-en-1-yl isobutyrate (3c)**: Acrolein (95%, 7.14 mmol, 107 mlm, 1.00 equiv) was dissolved in dry DCM (85 mL) and cooled to −20 °C using an acetone/liquid N2, cooling bath. First, isobutyryl bromide (9.03 g, 101 mmol, 0.95 eq) followed by anhydrous ZnCl2 (0.15 g, 1.07 mmol, 0.01 eq) was added. The reaction mixture was stirred and allowed to warm by lowering the cooling bath until −15 °C, when an exothermic reaction caused warming up to +10 °C. The flask was reheated in the cooling bath and the temperature was kept under −10 °C for 1 h. A sample (micro workup with EtOAc and aq. NaHCO3 and drying with MgSO4) for analysis via 1H NMR was taken, confirming complete conversion of starting material to the target products. Under cooling H2O (40 mL) was added (temperature rose to −10 °C), which led to the formation of a white precipitate. Layers were separated and the organic layer was washed with H2O (50 mL) and sat. NaHCO3 (until basic pH). The organic layer was washed with brine, dried over MgSO4 and the solvent evaporated, leaving a brown liquid (17.3 g) which was purified by distillation (bp 43 °C, 0.4 mbar) to give pure target compound 3c as colorless liquid (9.00 g, 41%): ratio of E/Z = 1:1.4; (E)-isomer.
naphthoic acid was added to the reaction mixture. The previously formed precipitate got dissolved and stirring was continued at rt for 1 h. The solvent was evaporated and the residue was treated with Et2O/hexane (1:1, 25 mL), which led to the formation of a lot of precipitate. The mixture was allowed to cool to rt, was filtered, and the solvent was evaporated leaving a slightly yellow, highly viscous oil (2.00 g). The crude material was purified via column chromatography on silica gel (40 g, DCM/MeOH 9:1) to give pure ε-erythroside (2.02 g, quant.) according to NMR, observed in a mixture of two furano forms and around ∼10% of the open chain form as hydrate which is consistent with the literature.4-Formyl-2,3-O-isopropylidene-ε-erythroside (7). Solid SO3- NaOAc (14% w/w), 52 g, 2.00 equiv) was added to a solution of 3,4-O-isopropylidene ε-arabinose2 2 (3.20 g, 16.8 mmol, 1.00 equiv) in DCM (65 mL) in one portion at the rt. The reaction was closed and shaken vigorously. After stirring 30 min at room temperature, reaction monitoring via TLC (LP/ EtOAc 1:1) showed complete conversion of starting material to a more apolar product (staining blue; staining different). The reaction mixture was filtered and the silica gel was washed with fresh DCM (250 mL). After evaporation of the solvent, the product 7 was obtained as a colorless oil in good purity and used without further purification (2.50 g, 79%); Rf 0.58 (LP/EtOAc 1:1); 1H NMR (400 MHz, CDCl3) δ 6.96 (d, J = 2.2 Hz, 1H, H1), 8.01 (q, J = 0.8 Hz, 1H, OCHO), 4.58 (ddd, J = 8.3, 5.1, 3.5 Hz, 1H, H3), 4.44 (m, 2H, H4 and H2), 2.17 (d, J = 12.2, 5.1, 0.8 Hz, 1H, H7), 1.45 (s, 3H, CH3) ppm. 13C NMR (101 MHz, CDCl3) δ 163.7 (C=O (OZ)), 139.6 (C=O (OZ)), 137.8 (C=O (OZ)), 134.84 (ArCH), 134.78 (ArCH), 133.98 (ArC), 131.74 (ArC), 131.72 (ArC), 131.42 (ArCH), 131.40 (ArCH), 128.88 (ArCH), 128.86 (ArCH), 128.5 (ArCH), 128.47 (ArCH), 126.7 (ArCH), 126.6 (ArCH), 125.72 (ArCH), 125.67 (ArC), 124.85 (ArCH), 124.65 (ArCH), 124.56 (ArCH), 111.9 (C=CH-E (E)), 110.1 (C=CH-Z (Z)), 24.0 (CH3-Br (Z)).

ε-Erythroside (6). Acetone S10 (2.70 g, 16.9 mmol, 1.00 equiv) was taken up in H2O (27 mL) and Dowex-H+ (freshly washed with H2O) was added and the mixture was heated to 80 °C for around 30 min. The mixture was allowed to cool to rt, was filtered over Celite, washed with fresh water (3 × ) and was lyophilized to give pure ε-erythroside (2.02 g, quant.) according to NMR, observed in a mixture of two furano forms and around ∼10% of the open chain form as hydrate which is consistent with the literature. J. Org. Chem. DOI: 10.1021/acs.joc.7b03063
and then bromopropenyl acetate (20.5 mg, 0.10 equiv) was added. The reaction mixture was neutralized with Dowex-H\(^+\) resin and filtered. Evaporation of the solvent gave deacetylated enolate species 16b as a colorless oil (72 mg, 0.30 mmol, as a solution in little EtOAc; R\(_{0.30}\) (CHCl\(_3\)/MeOH/H\(_2\)O 4:1:1), 0.16 (0.16 mg, 0.01 equiv) was dissolved in dry MeOH (10 mL) and NaOMe (2 mg, 0.04 mmol, 0.10 equiv) was added. The reaction mixture was heated to 45 °C in a round-bottom flask. In immediate succession, indium (2.25 g, 19.6 mmol, 4.00 equiv), freshly distilled bromopropenyl acetate 3a (5.26 g, 29.41 mmol, 6.00 equiv) and subsequently crude aldehyde 15 (<4.9 mmol, as a solution in little EtOAc) were added in one portion and the mixture was stirred at 45 °C. TLC analysis (LP/ EtOAc 1:1) showed complete conversion of starting material to a very polar spot (LP/EtOAc 3:1; DCM/MeOH 4:1). The reaction mixture was neutralized with Dowex-H\(^+\) resin and then filtered. Evaporation of the solvent gave deacetylated enolate species 16b as a colorless oil (72 mg, 0.30 mmol, as a solution in little EtOAc; R\(_{0.30}\) (CHCl\(_3\)/MeOH/H\(_2\)O 4:1:1).
was stirred for ten min, before it was diluted with EtOAc (200 mL) and washed with ice-cold 1 N HCl water, sat. aq. NaHCO₃ brine and dried over Na₂SO₄. Solvent was evaporated and the residue was taken up in dry MeOH (40 mL) and NaOMe (2 mg, 0.04 mmol, 0.10 equiv) was added. The reaction mixture was stirred at rt for 20 min, when reaction monitoring via TLC (LP/EtOAc 1:1; DCM/MeOH 4:1) showed complete conversion to a more polar spot. The reaction mixture was neutralized with Dowex-H⁺ resin and filtered. After the solvent was evaporated, the residue was taken up in dry MeOH (40 mL), fresh Dowex-H⁺ (4 g) added and stirred at rt overnight, when TLC analysis (DCM/MeOH 5:1) showed complete conversion to unprotected enolites. The resin was filtered and solvent evaporated. A pure fraction of the main isomer, talo-enolite 16c was isolated by recrystallization in dry EtOH (7 mL) as a white, highly crystalline solid (150 mg, 17%). The remaining isomers were isolated as a mixture from the mother liquid via flash column chromatography (45 g SiO₂, DCM/MeOH 6:1 → 2:1) as white solid. Overall yield of isolated enolites 16a–d: 550 mg, 63% (from 4-O-acetyl-3,2-O-isopropylidene-D-threitol). Ratio of isomers (via 1H NMR): talo (16c) 394 mg (72%), galacto (16d) 116 mg (21%), gulo (16a) 29 mg (5%), ido (16b) 10 mg (2%); Analytical data for 16c (talo): m.p.: 146–147°C (EtOH); Rf 0.23 (DCM/MeOH 5:1); [α]D +8.0 (+, 1.0, MeOH); 1H NMR (400 MHz, MeOD) δ 6.02 (d, J = 17.2, 10.5, 6.7 Hz, H1, H2), 5.32 (dd, J = 17.3, 2.1, 1.3 Hz, H1, H3a), 5.21 (dd, J = 10.5, 2.1, 1.1 Hz, H1, H3b), 4.29 (dd, J = 7.0, 4.7, 1.3 Hz, H3), 3.91 (td, J = 6.3, 1.7 Hz, H2, H3), 3.70 (dd, J = 4.7, 4.4, 1.7 Hz, H4, H5a), 3.62 (d, J = 6.3 Hz, H2, H5a/b), 3.53 (dd, J = 8.4, 1.6 Hz, H1, H5b); 13C NMR (101 MHz, MeOD) δ 138.3 (C2), 117.2 (C1), 75.4 (C3), 74.8 (C4), 72.7 (C5), 71.9 (C6), 64.7 (C7). HRMS (ESI-TOF) m/z [M + H]+ calculated for C17H24NaO10 411.1262, found 411.1267. Signals marked with an asterisk could not be assigned unambiguously.

β-Gulose (18). β-gulo-Heptenitol 16a (300 mg, 1.69 mmol, containing ~10% β-talo-isomer 16c) was subjected to ozonolysis (general method 1) to give β-gulose 18 (300 mg, quant containing ~10% β-talo-20): Rf 0.28 (CHCl₃/MeOH/H₂O 14:6:1); 1H NMR (400 MHz, D₂O) δ 4.89 (d, J = 8.4 Hz, 1H, H1), 4.07 (t, J = 3.5 Hz, 1H, H3), 4.00 (dd, J = 6.8, 5.4, 1.4 Hz, 1H, H5), 3.83–3.80 (m, 1H, H4), 3.75 (dd, J = 6.2, 2.0 Hz, 2H, H6a/b), 3.63 (dd, J = 8.4, 3.4, 0.5 Hz, 1H, H2); 13C NMR (101 MHz, D₂O) δ 94.4 (C1), 74.4 (C5), 71.8 (C3), 70.0 (C4), 69.7 (C2), 61.6 (C6). HRMS (ESI-TOF) m/z [M + COOH]⁺ calculated for C₁₀H₁₂O₅ 225.0616, found 225.0632; Spectral data is in accordance with commercially available β-gulose (see Supporting Information).

β-Idose (19). β-ido-Heptenitol 16b (70 mg, 0.39 mmol) was subjected to ozonolysis (general method 1) to give β-idose 19 (70 mg, quant.): Rf 0.30 (CHCl₃/MeOH/H₂O 14:6:1); [α]D +31 (+0.7, H₂O, 24 h), commercial sample: +11 (+1.0, H₂O); Spectral data is in accordance with commercially available β-idose (see Supporting Information).

β-Talose (20). β-talo-Heptenitol 16c (100 mg, 0.56 mmol) was subjected to ozonolysis (general method 1) to give β-talose 20 (100 mg, quant.): Rf 0.22 (CHCl₃/MeOH/H₂O 14:6:1); [α]D +33 (+1.0, H₂O, 18 h), lit. 8a 25 (+1.0, H₂O); Spectral data in accordance with a commercially sample of β-talose (see Supporting Information).

β-Talose (20) and β-Galactose (21). A mixture of β-talo-heptenitol 16c and β-galacto-heptenitol 16d (82.2, 60 mg, 0.34 mmol) was subjected to ozonolysis (general method 1) to give a mixture of β-talose 20 and β-galactose 21 (61 mg, quant.): Rf 0.22 (CHCl₃/MeOH/H₂O 14:6:1); Spectral data in accordance with a commercially sample of β-talose and β-galactose (see Supporting Information).

β-Idoprop-1-en-1-yl pivatele (22). Chloropropenyl pivatele 32 (200 g, 1.13 mmol, 1.00 equiv) was dissolved in acetone (4 mL) and added to a stirred solution of NaI (3.40g, 22.6 mmol, 2.00 equiv) in acetone (20 mL). A strong exotherm was observed at the beginning of the addition and the solution turned yellow. Further addition was done under water bath cooling. The reaction mixture was stirred at rt and under exclusion of light. After 1 h a small sample was diluted with Et₂O washed with water and brine, dried over Na₂SO₄ and was evaporated to and analyzed by 1H NMR to confirm full conversion to the target compound. The reaction mixture was poured into Et₂O (∼100 mL) and the filtered precipitate was filtered and washed with fresh Et₂O. The filtrate was washed with water, brine, dried over Na₂SO₄ and evaporated to leave a crude material (2.7 g, 89%) as a red liquid, according to 1H and 13C NMR the target compound 22 in sufficient purity to be subjected to the acetylation experiments without prolonged storage. ratio of E/Z 1:2; (E)-isomer 1H NMR (400 MHz, CDCl₃) δ 7.41 (dt, J = 12.3, 1.0 Hz, 1H, H=CH−O), 5.76 (dt, J = 12.3, 8.7 Hz, 1H, H=CH−CH=CH−), 3.90 (dd, J = 8.7, 1.0 Hz, 2H, CH₂−I), 1.23 (s, 9H, C(CH₃)₃), 1.35 (1H NMR (400 MHz, CDCl₃) δ 7.11 (d, J = 6.1 Hz, 1H, H=CH−O), 5.29 (dd, J = 8.7, 6.1 Hz, 1H, H=CH−CH=), 3.96 (dd, J = 8.7, 0.7 Hz, 2H, CH₂−I), 1.30 (s, 9H, C(CH₃)₃), 15C NMR (101 MHz, CDCl₃) δ 174.7 (C=O), 138.4 (=CH−O) 112.9 (=CH−CH=), 38.9 (C(CH₃)₂), 27.0 (C(CH₃)₂), 17.0 (CH=−I). (Z)-isomer: 1H NMR (400 MHz, CDCl₃) δ 6.11 (d, J = 6.1 Hz, 1H, H=CH−O), 5.29 (dd, J = 8.7, 6.1 Hz, 1H, H=CH−CH=), 3.96 (dd, J = 8.7, 0.7 Hz, 2H, CH₂−I), 1.30 (s, 9H, C(CH₃)₃), 15C NMR (101 MHz, CDCl₃) δ 174.7 (C=O), 137.3 (=CH−O), 111.1 (=CH−CH=), 39.3 (C(CH₃)₂), 27.2 (C(CH₃)₂), 4.7 (CH=−I).

ASSOCIATED CONTENT

*SUPPORTING INFORMATION*

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.7b03063.

Details of the quantification of the enol isomers 16a–d and 17a–d via 1H NMR. Detailed investigation of the fate of reagents 3a and 23 under the reaction conditions.

1H NMR and 13C NMR spectra for known and new...
compounds (3c–d, 6–7, 8a–c, 9a–b, 15, 16a–d, 17a–b, and 22) and comparisons of $^1$H NMR and $^{13}$C NMR spectra of synthesized and commercial samples of compounds 10–13 and 18–21 (PDF)

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**Notes**

The authors declare no competing financial interest.

**DEDICATION**

Dedicated to the memory of Prof. Walther Schmid.

**ACKNOWLEDGMENTS**

We thank the Austrian Science Fund FWF for financial support (Grants: J 3449-N28).

**REFERENCES**


(2) Collins, P.; Ferrier, R. Monosaccharides: Their Chemistry and Their Roles in Natural Products; Wiley, 1995.


(25) It is noteworthy that, for the conversion of the corresponding primary alcohol to aldehyde 15, from a variety of oxidation conditions only a protocol with IBX in EtOAc was found applicable for our purpose as it required only filtration and concentration which prevented the decomposition of very labile aldehyde 15 otherwise observed.

(26) Due to insufficient resolution at the GC-level, quantification was based on the $^1$H-NMRs (allylic proton) of crude enitol mixtures which were obtained from separate small scale experiments processed by a passage over a short bed of SiO2 and collection of all entitol fractions.


(30) Similar observations are hinted at in the original study (Palmelund 2005) as some of the investigated hexoses required a more finely dispersed quality of indium—increasing the surface and tentatively the initial rate of organyl formation—to achieve clean and full conversion which was reported to be unsuccessful with standard indium quality at prolonged reaction times.


(33) Acyloxyallylations performed with zinc were acetylated using Azo in pyridine, followed by acidic aqueous workup to remove all inorganics.


