

Practical and Catalytic Synthesis of 1,5-Anhydrohex-1-en-3-uloses

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Abstract: A practical and catalytic method for the preparation of 1,5-anhydrohex-1-en-3-uloses based on hydrogen transfer of D-glucals by catalytic amount of palladium complex in the presence of olefinic compounds such as ethylene and vinyl acetate has been disclosed.
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INTRODUCTION

Hexenuloses have played an important role in carbohydrate synthesis.¹ Among these, 1,5-anhydrohex-1-en-3-ulose derivatives are of particular interest, because the 1,4-addition allows the carbon-carbon bond formation at the anomeric center which leads to the formation of 2-deoxy-C-glycosides.^{2,3} One general method for incorporating the α,β -unsaturated moiety is the oxidation of allylic alcohols. Actually, some stoichiometric oxidants such as chromium, manganese, and palladium salts have been widely used for this purpose.^{4,5} However, they are sometimes toxic and the use of these reagents induces hazardous problems. The use of expensive palladium compounds cannot become a truly useful synthetic method. Therefore, the development of catalytic process has been strongly desired.⁶ Transition metals have been used for the transformation of alcohols into carbonyl compounds in organic synthesis.⁷ Among the transition metal complexes, a Pd(II) complex such as PdCl_2 and $\text{Pd}(\text{OAc})_2$ has been widely used in homogeneous oxidation. The oxidation of simple alcohols with palladium (II) salts was first reported by Lloyd in 1967.⁸ He revealed that primary and secondary alcohols were oxidized to the corresponding acetals and ketones by PdCl_2 under an oxygen atmosphere in the presence of a reoxidant such as CuCl_2 and $\text{Cu}(\text{NO}_3)_2$. After this report, Schwartz *et al.* reported homogeneous oxidation of secondary alcohols to ketones by a catalytic amount of $\text{PdCl}_2 \cdot \text{NaOAc}$ in the presence of molecular oxygen as the sole reoxidant.⁹ Very recently, Uemura and his co-workers reported $\text{Pd}(\text{OAc})_2$ -catalyzed oxidation of alcohols by molecular oxygen in the presence of pyridine and molecular sieves (MS) 3A.¹⁰ A similar type of palladium-catalyzed oxidation of alcohols was also reported by Peterson and Larock.¹¹ These oxidation methods require molecular oxygen in order to achieve the catalytic effect of palladium in the process.

In 1993, Czernecki and co-workers reported the oxidation of allylic alcohol of D-glucal (1) with a stoichiometric amount of $\text{Pd}(\text{OAc})_2$ in aqueous DMF (1% H_2O). However, they disclosed that several attempts

at oxidation with a catalytic amount of palladium acetate in the presence of copper acetate as reoxidant were unsuccessful.

Here we would like to report a practical and catalytic method for the preparation of 1,5-anhydrohex-1-en-3-uloses based on hydrogen transfer of D-glucals by catalytic amount of palladium complex in the presence of olefinic compounds such as ethylene and vinyl acetate.

RESULTS AND DISCUSSION

During the course of our study on C-glycosidation of unprotected D-glucals¹² and the synthesis of unprotected branched-chain sugars¹³ using palladium catalyst, we found D-glucal was converted into a mixture of approximately equimolar amounts of an oxidation product of allylic alcohol (1,5-anhydrohex-1-en-3-ulose) **2** and hydrogenated product **3** by treatment with a catalytic amount of Pd(OAc)₂ in CH₃CN (eq. 1).¹⁴ The obtained results are summarized in Table 1. The yields in Table 1 represent the combined yield of **2** and **3**, and the ratio of **2/3** was determined by ¹H NMR analysis after acetylation. The ratio of **2/3** thus calculated was fully consistent with the isolated yields of **2** and **3**. For example, the reaction of **1** with 5 mol% of Pd(OAc)₂ afforded the combined yield of **2** and **3** in 88% in a ratio of 54.5:45.5 (determined by ¹H NMR), whereas the independent reaction gave **2** and **3** in 44% and 37% isolated yield, respectively. Under neutral and mild

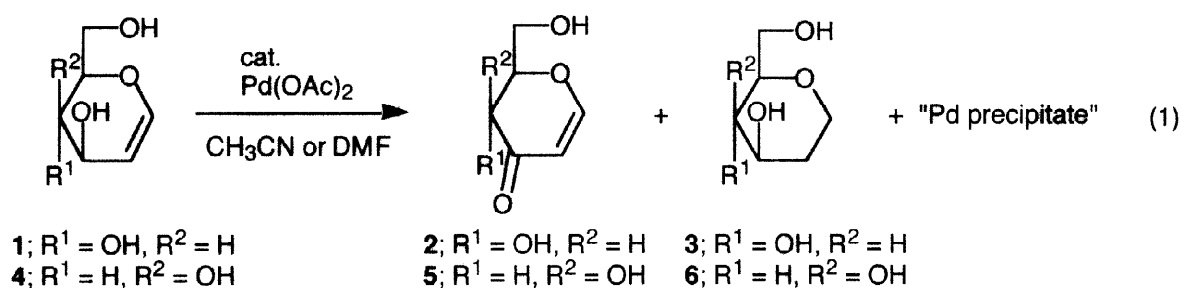


Table 1. Catalytic oxidation of D-glycal (**1,4**) by palladium complexes^a

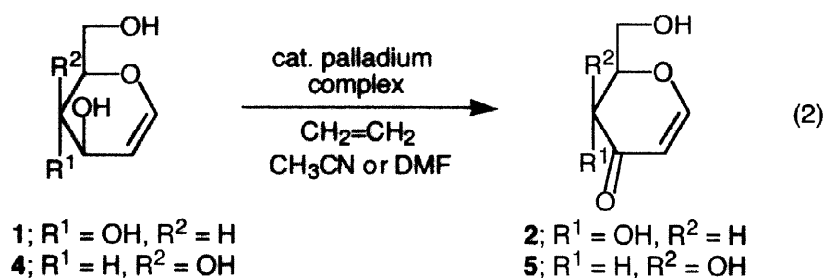
Entry	Glycal	Palladium (mol%)	Solvent	Conditions		Product
				temp/°C	time/h	% yield ^b (2/3)
1	1	Pd(OAc) ₂ (1)	CH ₃ CN	25	96	72 (50.2/49.8)
2	1	Pd(OAc) ₂ (2)	CH ₃ CN	25	95	90 (50.5/49.5)
3	1	Pd(OAc) ₂ (5)	CH ₃ CN	25	23	88 (54.5/45.5)
4	1	Pd(OAc) ₂ (5)	CH ₃ CN	25	25	44 (2), 37 (3) ^c
5	1	Pd(OAc) ₂ (5)	DMF	20	3	88 (57/43)
6	1	PdCl ₂ (5)–NaOAc (10)	CH ₃ CN	25	60	92 (52.6/47.4)
7	1	Pd precipitate (7) ^d	CH ₃ CN	25	17	50 (2), 49 (3) ^c
8	4	Pd(OAc) ₂ (5)	DMF	25	5	49 (5), 36 (6) ^c

(Footnotes of Table 1) ^a All reactions were carried out under argon atmosphere. ^b The combined yield after acetylation. The ratio was determined by ¹H NMR analyses. ^c Isolated yield after silica-gel column chromatography. ^d Weight %.

conditions, the use of 1–2 mol% of Pd(OAc)₂ afforded satisfactory yield (72–90%), though prolonged reaction time (96 h) was required. Among the solvents we examined, CH₃CN and DMF gave the best results. Considering the operation for recovery of the palladium precipitate by centrifugation, we selected CH₃CN as a solvent. In the case of D-galactal (**4**), the reaction in DMF proceeded more effectively than in CH₃CN because of the solubility of **4**. The combined PdCl₂–NaOAc catalyst system afforded similar results as in the case of Pd(OAc)₂; however, the use of PdCl₂ alone proved to be ineffective for the present reaction.

It should be mentioned that precipitation of the palladium complex was observed immediately after mixing D-glucal and Pd(OAc)₂ and the solution became heterogeneous. The fact that the only a catalytic amount of Pd(OAc)₂ was required to complete the reaction suggested that the palladium precipitate thus formed would be reusable. So, we next examined the reuse of this palladium complex, and found the recovered palladium precipitate was also effective in the next reaction. The yield of the second and third run (the use of 7 weight% of palladium precipitate) was comparable to that of the first run (first run, **2** (50%), **3** (49%); second run, **2** (39%), **3** (39%); third run, **2** (48%), **3** (47%)); thus, the continuous use of the palladium catalyst was realized. In these cases, the ratio of **2** and **3** was fairly equal compared with the reactions in which Pd(OAc)₂ was added. These results indicate that, after oxidation of D-glucal forming enone by Pd(OAc)₂ in the initial step, the formed palladium compound caused some type of hydrogen transfer reaction,¹⁵ that is, one molecule of D-glucal was dehydrogenated (oxidized) and another hydrogenated (reduced).

The above-mentioned redox reaction of D-glucal is interesting; however, the yield of the desired oxidation product was up to 50%, which was unsatisfactory from the synthetic viewpoint. Therefore, we then aimed at suppression of the generation of reduced glucal **3**. We expected that ethylene might work as a simple and sacrificial olefin and we employed the reaction under ethylene atmosphere. As expected, when D-glucal was treated with the above palladium precipitate catalyst obtained from the reaction shown in eq. 1 under ethylene atmosphere, the formation of hydrogenated product **3** was suppressed, and enone product **2** was obtained in high yield (eq. 2). The treatment of D-galactal **4** with the above palladium catalyst in DMF under ethylene atmosphere at room temperature for 45 h gave the oxidation product in 81% yield. In this reaction also the formation of a hydrogenated product was not observed. Furthermore, epimerization at the C-4 position was not observed, which was quite in contrast to the result of a stoichiometric reaction.⁵ To our knowledge, this is the first example of palladium-catalyzed catalytic oxidation of alcohols to ketones in the absence of a reoxidant such as molecular oxygen. The obtained results are summarized in Table 2. Pd(OAc)₂ also worked as an oxidizing reagent though it was less reactive than the above palladium precipitate. That is, D-glucal was converted to the oxidation product only in moderate yield (62–66%) even by the use of 10 mol% of Pd(OAc)₂ under ethylene atmosphere, and in order to attain satisfactory yield, the use of palladium precipitate obtained from the reaction eq.1 was required.

Table 2. Oxidation of D-glycal (1,4) to enones (2,5).^a

Entry	Glycal	Palladium ^b	Solvent	Conditions		Product (% yield) ^c
				temp/°C	time/h	
1	1	A	CH ₃ CN	50	30	2 (98)
2	1	B	CH ₃ CN	60	30	2 (62) ^d
3	4	A	DMF	50	96	5 (81)
4	4	B	DMF	25	45	5 (66) ^e

^a All reactions were carried out under ethylene atmosphere. In all cases, the formation of a hydrogenation product (3, 6) was not observed. ^b A: palladium precipitate (7–8 weight%), B: Pd(OAc)₂ (10 mol%). ^c Isolated yield after acetylation unless otherwise noted. ^d Isolated yield as unprotected enone 2. ^e Starting material was recovered in 17% yield.

Therefore, among more efficient system in which Pd(OAc)₂ can be used directly as an oxidizing reagent, we examined the effect of the nature of a variety of sacrificial olefins on reactivity. Some of the obtained results are summarized in Table 3. All reactions were carried out in acetonitrile at 50 °C in the presence of 3 equiv. of sacrificial olefinic compounds. The yields of the product and the ratio of oxidized product and reduced one was determined after acetylation.

As shown in Table 3, it was clear that in some cases the addition of olefinic compounds suppressed the formation of hydrogenated product 3. Among the olefinic compounds we examined, vinyl acetate was found to be most effective with respects to chemical yield and selectivity. The addition of 3,4-dihydro-2H-pyran and styrene retarded the oxidation reaction.

We then examined the effect of solvent and amount of vinyl acetate on reactivity and selectivity. Table 4 shows the obtained results. The reaction in acetonitrile proceeded effectively to give the products in high yield (>90% yield), while the reaction in DMF did not furnish the reaction completely, though the formation of saturated product was not observed. The use of mixed solvent (CH₃CN/DMF; 2/1, 1/1, 1/2) resulted in the same outcome with the reaction in DMF, that is, the yield was moderate (40–48% yield; recovery of 1 was 28–52%), though the selectivity was perfect. The addition of 1 equiv. of vinyl acetate proved to be effective to suppress the formation of hydrogenated product (2/3 = 90/10). The ratio of 2/3 raised up to 97/3 when 5 equiv. of vinyl acetate was added. It should be noted that the reaction without solvent also proceeded smoothly to give the product in high yield, though the selectivity of 2/3 was slightly decreased (2/3 = 88/12).

Table 3. Catalytic oxidation of D-glucal (**1**) by Pd(OAc)₂^a

Entry	Glucal	palladium (mol%)	olefinic compound	% yield ^b (2/3)
1	1	Pd(OAc) ₂ (5)	none	88 (55/45)
2	1	Pd(OAc) ₂ (5)	vinyl acetate	96 (94/6)
3	1	Pd(OAc) ₂ (5)	2,3-dihydrofuran	95 (74/26)
4	1	Pd(OAc) ₂ (5)	3,4-dihydro-2H-pyran	0 (–)
5	1	Pd(OAc) ₂ (5)	styrene	trace (–)

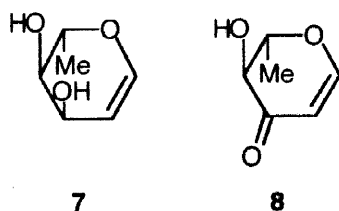
^a All reactions were carried out in acetonitrile at 50 °C using 3 equiv. of olefinic compounds. ^b The combined yield after acetylation. The ratio was determined by ¹H NMR analyses.

The treatment of D-galactal **4** with 5 mol% of Pd(OAc)₂ in the presence of vinyl acetate also proceeded effectively in acetonitrile and without solvent. Under the latter condition, the oxidized product and hydrogenated one were obtained in 71% and 3% yield, respectively (run 8 in Table 2). Furthermore, it should be mentioned that epimerization at C-4 position was not detected. In the case of L-rhamnal **6**, only the formation of oxidized product **8** was observed.¹⁶

Table 4. Catalytic oxidation of D-glycal (**1**, **4** and **6**) by Pd(OAc)₂ in the presence of vinyl acetate^a

Entry	Glycal	Palladium (mol%)	Solvent	equiv. of vinyl acetate	% Yield ^b (2/3)
1	1	Pd(OAc) ₂ (5)	CH ₃ CN	0	88 (55/45)
2	1	Pd(OAc) ₂ (5)	CH ₃ CN	1	96 (90/10)
3	1	Pd(OAc) ₂ (5)	CH ₃ CN	3	90 (94/6)
4	1	Pd(OAc) ₂ (3)	CH ₃ CN	3	83 (2) ^c
5	1	Pd(OAc) ₂ (5)	CH ₃ CN	5	90 (97/3)
6	1	Pd(OAc) ₂ (5)	DMF	3	48 (100/0)
7	1	Pd(OAc) ₂ (5)	none	10	79 (88/12)
8	4	Pd(OAc) ₂ (5)	CH ₃ CN	3	78 (88/12)
9	4	Pd(OAc) ₂ (5)	none	10	74 (96/4)
10	7	Pd(OAc) ₂ (5)	none	10	70 (100/0)

^a All reactions were carried out under argon atmosphere. ^b The combined yield after acetylation. The ratio was determined by ¹H NMR analyses. ^c Isolated yield after silica-gel column chromatography.



This reaction apparently involves the hydrogen transfer of D-glycals to vinyl acetate. The formation of ethyl acetate was confirmed by GLC and ^1H NMR analyses. The ratio of the oxidation product **2** and hydrogenated product **3** would be dependent on the tendency of the ease of suffering hydrogenation of added sacrificial olefins. The palladium-catalyzed oxidation is initiated by the complexation of the alcohol to the Pd(II) catalyst involving formation of a palladium alkoxide which then undergoes β -hydride transfer from C to Pd to yield the carbonyl product and Pd(II)-hydride complex (H-Pd(II)-OAc). If this Pd-hydride species then undergoes reductive elimination to form Pd(0), a reoxidant such as molecular oxygen should be necessary to regenerate the Pd(II) species. In the present case, however, the forming Pd(II)-hydride complex is supposedly capable of oxidizing another mol of alcohol to the carbonyl compound, and palladium dihydride will be formed. This palladium dihydride complex then converts **1** to hydrogenated product **3**, and Pd(II) would be regenerated, which oxidizes **1** to **2** again. Another plausible mechanism to regenerate the Pd(II) species would include the process in which H-Pd(II)-OAc coordinates to olefin, followed by insertion, and the resulting palladium compound will react with HOAc to generate the reduced product and Pd(OAc)₂. Thus, a catalytic amount of Pd(OAc)₂ was adequate to produce **2** and **3** in high yield in approximately equal amounts. In the present case, however, H-Pd(II)-OAc would coordinates to vinyl acetate, followed by insertion, and the resulting compound possessing a Pd- σ bond will react with HOAc to generate the ethyl acetate and regenerate Pd(OAc)₂.

CONCLUSION

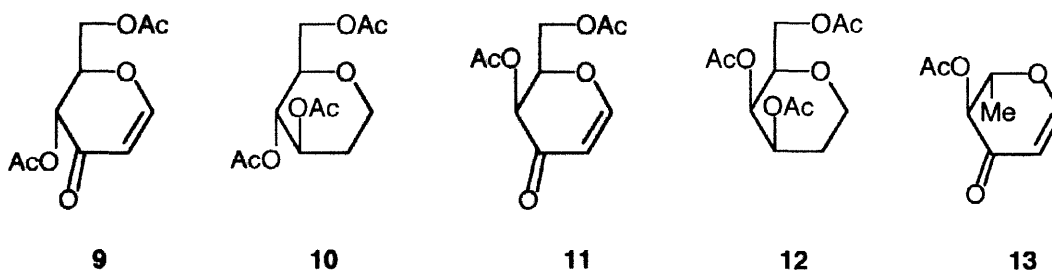
In conclusion, we have developed a practical and catalytic method for the preparation of 1,5-anhydrohex-1-en-3-uloses by the treatment of D-glycals with catalytic amount of palladium complexes in the presence of vinyl acetate or ethylene. The present "vinyl acetate" method is advantageous over "ethylene" method from the standpoint of reactivity and availability of the catalyst. That is, Pd(OAc)₂ itself can be used as a palladium source. On the other hand, in the case of "ethylene" method, the use of Pd(OAc)₂ resulted in low reactivity, so the use of palladium precipitate generated from eq. 1 was required to obtain satisfactory reactivity. This new method represents a new process in which the palladium (II) species, required for the oxidation of the alcohol, is regenerated and shows unique characteristic features compared with the conventional aerobic method.

Experimental Section

General and Materials. All melting points were uncorrected. ^1H NMR spectra were recorded on a Hitachi R-250 Fourier Transfer NMR spectrometer at 250 MHz with tetramethylsilane used as an internal standard. The chemical shifts are reported in ppm on δ scale downfield from tetramethylsilane, and signal patterns are indicated as follows: s, singlet; d, doublet; t, triplet; m, multiplet; br, broad peak. ^{13}C NMR spectra were recorded on a Hitachi R-250 Fourier Transfer NMR spectrometer at 62.9 MHz. The chemical shifts are reported in ppm with chloroform- δ (77.0 ppm) or tetramethylsilane as an internal standard. IR spectra were measured on Nicolet Impact 410. Optical rotations were measured by SEPA-300 (HORIBA) in solution in a 1-

dm cell. Elemental analyses were performed on Yanaco CHN CORDER MT-5. Preparative column chromatography was carried out on a Fuji-Davison BW-820 or Wacogel-300 column. Thin layer chromatography (TLC): Foil plates, silica gel 60 F₂₅₄ (Merck; layer thickness 0.2 mm). All experiments were carried out under argon atmosphere. Acetonitrile was distilled from CaH₂. D-Glucal (1,5-anhydro-2-deoxy-D-arabino-hex-1-enitol), tri-*O*-acetyl-D-galactal, and 3,4-di-*O*-acetyl-L-rhamnal (3,4-di-*O*-acetyl-6-deoxy-L-glucal) were purchased from Aldrich. D-galactal and L-rhamnal were prepared according to the reported procedure.⁴ Pd(OAc)₂ was purchased from Wako and used without further purification.

Typical Procedure (Entry 4 in Table 4). A mixture of palladium acetate (216 mg, 0.96 mmol), D-glucal (4.88 g, 33.4 mmol), vinyl acetate (9.5 mL, 100.3 mmol), and CH₃CN (20 mL) was stirred at 50 °C for 30 h. The black palladium solid was separated by centrifugation, and the solution was concentrated. Purification by silica-gel column chromatography using ethyl acetate as an eluent afforded 1,5-anhydro-2-deoxy-D-erythro-hex-1-en-3-ulose (**2**) (4.0 g, 83%).



1,5-Anhydro-2-deoxy-D-erythro-hex-1-en-3-ulose (2**):** colorless needles. *R_f* 0.39 (ethyl acetate); mp 89 °C (lit.⁴ 87–88 °C); [α]_D³⁰ +292.4 (*c* 1, H₂O) (lit.⁴ [α]_D²⁰ +297.5 (*c* 1, H₂O), lit.¹⁷ [α]_D²⁰ +283 (*c* 0.8, H₂O)); IR (KBr) 3350, 1660, 1605, 1420, 1280, 1120, 1040, 850 cm⁻¹; ¹H NMR (DMSO-*d*₆, 250 MHz) δ 3.7–3.8 (m, 2H), 4.1–4.12 (m, 2H), 5.0 (t, *J* = 5.8 Hz, 1H, OH(6)), 5.30 (d, *J* = 5.5 Hz, 1H), 5.62 (d, *J* = 4.4 Hz, 1H, OH(4)), 7.61 (d, *J* = 5.5 Hz, 1H); ¹³C NMR (CD₃OD) δ 61.9, 69.2, 85.1, 105.1, 165.6, 197.2. Anal. Calcd for C₆H₈O₄: C, 50.00; H, 5.59. Found: C, 49.76; H, 5.66.

4,6-di-*O*-Acetyl-1,5-Anhydro-2-deoxy-D-erythro-hex-1-en-3-ulose (9**):** colorless oil. *R_f* 0.53 (hexane–ethyl acetate 1:1); [α]_D³⁰ +245.6 (*c* 1, CHCl₃) (lit.⁴ [α]_D²⁰ +255 (*c* 1, CHCl₃); IR (neat) 1750, 1700, 1600, 1405, 1370, 1320, 1240, 1100, 1080, 1040, 960, 910, 880, 800 cm⁻¹; ¹H NMR (CDCl₃, 250 MHz) δ 2.02 (s, 3H), 2.12 (s, 3H), 4.38 (dd, *J* = 12.2 Hz, 2.4 Hz, 1H), 4.44 (dd, *J* = 12.2 Hz, 4.3 Hz, 1H), 4.62 (ddd, *J* = 2.4 Hz, 4.3 Hz, 12.7 Hz, 1H), 5.50 (d, *J* = 5.5 Hz, 1H), 5.55 (d, *J* = 12.7 Hz, 1H), 7.38 (d, *J* = 5.5 Hz, 1H); ¹³C NMR (CDCl₃) δ 19.2, 19.4, 60.2, 66.8, 76.5, 104.1, 161.3, 167.9, 169.1, 186.6. Anal. Calcd for C₁₀H₁₂O₆: C, 52.63; H, 5.30. Found: C, 52.34; H, 5.35.

D-*r*-2-Hydroxymethyl-tetrahydropyran-*t*-3,*c*-4-diol (3**):** colorless crystal. *R_f* 0.29 (acetone–ethyl acetate 2:1); mp 85 °C; [α]_D³⁰ +16.8 (*c* 1, H₂O); IR (KBr) 3390, 2955, 2930, 2880, 2870, 1660, 1440, 1380, 1100, 1040, 950, 900 cm⁻¹; ¹H NMR (DMSO-*d*₆, 250 MHz) δ 1.41 (dddd, *J* = 4.9 Hz, 11.9 Hz, 13.2 Hz, 13.4 Hz, 1H), 1.75 (ddd, *J* = 11.9 Hz, 5.2 Hz, 1.8 Hz, 1H), 2.94–2.95 (m, 2H), 3.2–3.5 (m, 3H), 3.66 (dd, *J* =

6.1 Hz, 11.6 Hz, 1H), 3.77 (dd, $J = 4.9$ Hz, 11.2 Hz, 1H), 4.39 (t, $J = 5.8$ Hz, 1H), 4.75 (d, $J = 4.3$ Hz, 1H), 4.79 (d, $J = 1.2$ Hz, 1H); ^{13}C NMR (CD_3OD) δ 34.7, 62.8, 66.2, 73.1, 73.7, 81.9. Anal. Calcd for $\text{C}_6\text{H}_{12}\text{O}_4 \cdot 1/16\text{H}_2\text{O}$: C, 48.27; H, 8.19. Found: C, 48.27; H, 8.37.

***t*-4-Acetoxy-*t*-2-acetoxymethyl-tetrahydropyran-*r*-3-yl acetate (10):** colorless oil. R_f 0.59 (hexane–ethyl acetate 1:1); $[\alpha]_D^{30} +28.0$ (c 1, CHCl_3); IR (neat) 2960, 2860, 1740, 1440, 1370, 1235, 1160, 1070, 1050, 940, 895, 870, 690, 600 cm^{-1} ; ^1H NMR (CDCl_3 , 250 MHz) δ 1.8–1.9 (m, 1H), 2.04 (s, 3H), 2.05 (s, 3H), 2.10 (s, 3H), 2.0–2.1 (m, 1H), 3.5–3.6 (m, 2H), 4.03 (dd, $J = 6.1$ Hz, 1.65 Hz, 1H), 4.14 (dd, $J = 2.1$ Hz, 12.1 Hz, 1H), 4.24 (dd, $J = 5.0$ Hz, 12.1 Hz, 1H), 4.9–5.0 (m, 2H). ^{13}C NMR (CDCl_3) δ 20.6, 20.7, 20.9, 30.9, 62.6, 65.3, 69.2, 72.2, 76.4, 169.7, 170.3, 170.7. Anal. Calcd for $\text{C}_{12}\text{H}_{18}\text{O}_7$: C, 52.55; H, 6.61. Found: C, 51.81; H, 6.66.

1,5-Anhydro-2-deoxy-D-threo-hex-1-en-3-ulose (5): colorless oil. R_f 0.33 (ethyl acetate); $[\alpha]_D^{30} +165.4$ (c 1, H_2O) (lit.⁴ $[\alpha]_D^{20} +54$ (c 1, H_2O)); IR (neat) 3400, 1670, 1590 cm^{-1} ; ^1H NMR ($\text{DMSO}-d_6$, 250 MHz) δ 3.70 (ddd, $J = 1.2$ Hz, 5.5 Hz, 5.6 Hz, 1H), 3.73 (ddd, $J = 2.4$ Hz, 5.5 Hz, 5.6 Hz, 1H), 3.82 (ddd, $J = 1.2$ Hz, 2.4 Hz, 4.0 Hz, 1H), 4.27 (m, 1H), 4.96 (dd, $J = 5.5$ Hz, 5.5 Hz, 1H), 5.29 (dd, $J = 6.1$ Hz, 1.2 Hz, 1H), 5.91 (d, $J = 5.5$ Hz, 1H), 7.57 (d, $J = 6.1$ Hz, 1H). ^{13}C NMR (CD_3OD) δ 60.3, 70.0, 84.1, 105.3, 165.0, 194.0. Anal. Calcd for $\text{C}_6\text{H}_8\text{O}_4 \cdot 1/4\text{H}_2\text{O}$: C, 48.49; H, 5.76. Found: C, 48.752; H, 5.83.

4,6-di-*O*-Acetyl-1,5-Anhydro-2-deoxy-D-threo-hex-1-en-3-ulose (11): oil. R_f 0.57 (hexane–ethyl acetate 1:1); $[\alpha]_D^{30} +68.8$ (c 1, CHCl_3) (lit.⁴ $[\alpha]_D^{20} +22.7$ (c 0.5, CHCl_3)); IR (neat) 1745, 1690, 1595, 1370, 1225, 1040, 760 cm^{-1} ; ^1H NMR (CDCl_3 , 250 MHz) δ 2.09 (s, 3H), 2.17 (s, 3H), 4.34 (dd, $J = 4.3$ Hz, 12.2 Hz, 1H), 4.42 (dd, $J = 7.3$ Hz, 12.2 Hz, 1H), 4.77 (dt, $J = 4.3$ Hz, 7.3 Hz, 1H), 5.51 (d, $J = 6.1$ Hz, 1H), 5.56 (d, $J = 4.3$ Hz, 1H), 7.35 (d, $J = 6.1$ Hz, 1H). ^{13}C NMR (CDCl_3) δ 20.4, 20.6, 60.6, 68.1, 77.8, 105.7, 161.8, 169.0, 170.2, 185.5. Anal. Calcd for $\text{C}_{10}\text{H}_{12}\text{O}_6$: C, 52.63; H, 5.30. Found: C, 52.48; H, 5.24.

D-*r*-2-Hydroxymethyl-tetrahydropyran-*c*-3,*c*-4-diol (6): colorless crystal. R_f 0.17 (acetone–ethyl acetate 1:1); mp 124–125 °C; $[\alpha]_D^{30} +48.5$ (c 0.8, H_2O); IR (KBr) 3300, 2980, 2960, 2890, 2860, 1470, 1440, 1365, 1190, 1150, 1100, 1040, 900, 810, 760, 685, 670 cm^{-1} ; ^1H NMR ($\text{DMSO}-d_6$, 250 MHz) δ 1.40 (ddd, $J = 1.8$ Hz, 4.9 Hz, 11.6 Hz, 1H), 1.74 (ddd, $J = 4.9$ Hz, 11.3 Hz, 11.6 Hz, 12.1 Hz, 1H), 3.1–3.3 (m, 2H), 3.4–3.6 (m, 4H), 3.78 (ddd, $J = 11.3$ Hz, 4.9 Hz, 1.5 Hz, 1H), 4.10 (d, $J = 4.3$ Hz, 1H), 4.48 (t, $J = 5.5$ Hz, 1H), 4.54 (d, $J = 6.1$ Hz, 1H). ^{13}C NMR (CD_3OD) δ 30.3, 63.8, 67.3, 70.1, 70.8, 81.1. Anal. Calcd for $\text{C}_6\text{H}_{12}\text{O}_4$: C, 48.64; H, 8.16. Found: C, 48.45; H, 8.21.

***c*-4-Acetoxy-*c*-2-acetoxymethyl-tetrahydropyran-*r*-3-yl acetate (12):** colorless oil. R_f 0.56 (hexane–ethyl acetate 1:1); $[\alpha]_D^{30} +49.9$ (c 1, CHCl_3); IR (neat) 2970, 2860, 1650, 1445, 1370, 1240, 1170, 1100, 1060, 900, 830, 740, 630, 610 cm^{-1} ; ^1H NMR (CDCl_3 , 250 MHz) δ 1.7–1.8 (m, 1H), 2.00 (s, 3H), 2.06 (s, 3H), 2.15 (s, 3H), 2.0–2.2 (m, 1H), 3.58 (dt, $J = 2.0$ Hz, 12.4 Hz, 1H), 3.75 (t, $J = 6.1$ Hz, 1H), 4.1–4.2 (m, 3H), 4.99 (ddd, $J = 3.2$ Hz, 5.0 Hz, 12.5 Hz, 1H), 5.31 (d, $J = 2.4$ Hz, 1H). ^{13}C NMR (CDCl_3) δ 20.5, 20.7, 26.1, 62.5, 65.7, 66.7, 69.5, 74.7, 169.9, 170.1, 170.4. Anal. Calcd for $\text{C}_{12}\text{H}_{18}\text{O}_7$: C,

52.55; H, 6.62. Found: C, 52.35; H, 6.71.

1,5-Anhydro-2,6-dideoxy-L-erythro-hex-1-en-3-ulose (8): colorless crystals. R_f 0.70 (hexane–ethyl acetate 1:1); mp 84–86 °C (lit.⁴ 92–93 °C, lit.¹⁸ 86 °C); $[\alpha]_D^{30}$ -244.6 (c 1, CH₃OH) (lit.⁴ $[\alpha]_D^{20}$ -244 (c 3, CH₃OH), lit.¹⁸ $[\alpha]_D^{20}$ -288 (c 1.3, CH₃OH)); IR (KBr) 3404, 3104, 2916, 2354, 1675, 1600, 1408, 1258, 1204, 1129, 1058, 1038, 863, 821 cm⁻¹; ¹H NMR (DMSO-d₆, 250 MHz) δ 1.31 (d, J = 6.1 Hz, 3H), 3.85 (dd, J = 4.9 Hz, 12.2 Hz, 1H), 4.20 (dq, J = 6.1 Hz, 12.2 Hz, 1H), 5.32 (d, J = 6.1 Hz, 1H), 5.64 (d, J = 4.9 Hz, 1H), 7.57 (d, J = 6.1 Hz, 1H). ¹³C NMR (CDCl₃) δ 17.5, 20.5, 73.1, 77.2, 105.1, 162.9, 169.4, 188.3. Anal. Calcd for C₆H₈O₃·1/16H₂O: C, 55.76; H, 6.34. Found: C, 55.73; H, 6.34.

4-O-Acetyl-1,5-Anhydro-2,6-dideoxy-L-erythro-hex-1-en-3-ulose (13): colorless crystals. R_f 0.70 (hexane–ethyl acetate 1:1); mp 64–65 °C (lit.⁴ 61–62 °C, lit.¹⁸ 62 °C); $[\alpha]_D^{21}$ -288.3 (c 0.7, CH₂Cl₂) (lit.⁴ $[\alpha]_D^{20}$ -272 (c 0.95, CH₂Cl₂), lit.¹⁸ $[\alpha]_D^{20}$ -277.9 (c 2.4, CH₂Cl₂)); IR (neat) 2358, 1746, 1679, 1600, 1408, 1375, 1263, 1241, 1204, 1121, 1087, 1046, 867, 804 cm⁻¹; ¹H NMR (CDCl₃, 250 MHz) δ 1.47 (d, J = 6.1 Hz, 3H), 2.20 (s, 3H), 4.51 (dq, J = 6.1 Hz, 12.7 Hz, 1H), 5.26 (d, J = 12.7 Hz, 1H), 5.45 (d, J = 5.5 Hz, 1H), 7.34 (d, J = 5.5 Hz, 1H). ¹³C NMR (CDCl₃) δ 17.5, 20.5, 73.1, 77.2, 105.1, 162.9, 169.4, 188.3. Anal. Calcd for C₈H₁₀O₄: C, 56.47; H, 5.92. Found: C, 56.36; H, 5.96.

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