(131 °C, 4 h, 82% yield) produced methoxatin triester **2**[4,13] probably via the aminoallene **11** and the corresponding imine, followed by electrocyclic ring closure and elimination of HCl. Hydrolysis to methoxatin (**1**) was effected with lithium hydroxide.[3]

Acknowledgment. This work was supported by a National Research Service Award (No. 2T32CA09112) from the National Cancer Institute, DHEW, the National Institutes of Health (Grant GM 09868), and Hoffmann-La Roche Inc. High-resolution mass spectra were provided by the facility, supported by the National Institutes of Health (Grant RR 00317) (Principle Investigator, Professor K. Biemann), from the Biotechnology Resources Branch, Division of Research Resources. We thank Ajinomoto Inc. for a gift of *o*-tyrosine.

(13) We are indebted to Professor J. B. Hendrickson and Dr. DeVries for an authentic sample of **2**.

Stereospecific Synthesis of Rhynchosporosides: A Family of Fungal Metabolites Causing Scald Disease in Barley and Other Grasses

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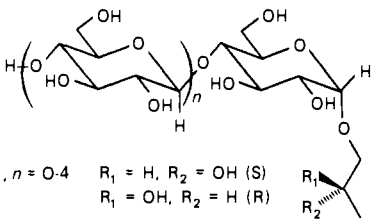
Received April 25, 1985

In addition to insect and weed pests, another major cause of destruction in plants used for food, fiber, and recreation originates from phytotoxin-producing fungi and bacteria. The rhynchnosporosides are a family of such destructive compounds produced by *Rhynchosporium secalis* and recognized over the last few years as the causal agents of scald disease in barley, rye, wheat, and other grasses.[1] Although the detection of these toxins was made as early as 1971 in Australia by Ayesu-Offei and Clare,[2] culture and isolation difficulties hampered elucidation of their structures until recently when investigations by Strobel in the USA and Auriol in France suggested the mixture of oligosaccharides (I) (n = 0–4, R and/or S series) were responsible for the phytotoxic



1, n = 0-4 R_1 = H, R_2 = OH (S); R_1 = OH, R_2 = H (R)

activity.[3] Syntheses of mono- and disaccharides were recently reported by the groups of Ogawa,[4a] Strobel,[4b] and Auriol,[4c] but the more potent, higher homologues still remain elusive to both full structural elucidation and synthesis. In view of the importance of these compounds and in an effort to assist in their isolation from their natural source, structural elucidation, and biological investigation we initiated a synthetic program directed toward these structures. In this paper we wish to report the first synthesis of six rhynchosporosides (I, n = 2–4, R and S series) by an efficient and stereospecific route based on our recently reported two-stage activation procedure for oligosaccharide synthesis.[5]

† Recipient of a Camille and Henry Dreyfus Teacher-Scholar Award, 1980–1985; J. S. Guggenheim Fellow, 1984–1985.

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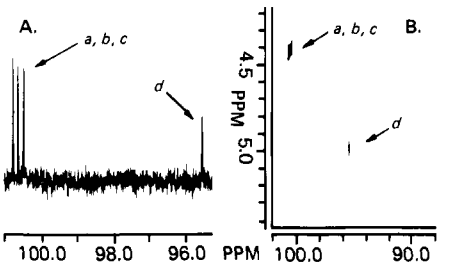

Figure 1. NMR Experiments with peracetylated [4*S*]-rhynchosporoside (Bruker AM-500, $CDCl_3$). (A) Expansion of the anomeric region of a 125.7-MHz ^1H-decoupled ^{13}C NMR spectrum showing the three β-linkages (signals a, b, and c) and the one α-linkage (signal d). (B) Contour plot of the anomeric region of a 125.7-MHz 2D ^1H–^{13}C heteronuclear chemical shift-correlated NMR spectrum showing the shifts for the anomeric carbons and protons (β-bonds, a, b, c; α-bond, d).

As in most oligo- and polysaccharide syntheses, the challenging issues in the present undertaking were (i) efficient and convenient couplings of the components of the chains and (ii) stereocontrol in the formation of the glycoside bonds. The mild, two-stage activation method involving phenylthio and fluoro sugars and the choice of suitable protecting groups and reaction medium allowed efficient, convenient, and stereospecific synthesis of both the S and the R series of tri-, tetra-, and pentasaccharides I. *Thus, β-glycoside bond specificity was secured by strategic placement of an acetoxy group at the 2-position (α)*[6] *and performing the coupling reaction in CH_2Cl_2, whereas α-glycoside bond specificity was observed when a benzyloxy group was present at the 2-position (α) and the glycosidation was performed in ether as solvent.*

Scheme I outlines the construction of the targeted rhynchosporosides **15a** ([3*R*]-rhynchosporoside)[8], **15b** ([3*S*]-rhynchosporoside), **19a** ([4R]-rhynchosporoside), **19b** ([4*S*]-rhynchosporoside), **25a** ([5*R*]-rhynchosporoside), and **25b** ([5*S*]-rhynchosporoside) from the simple building blocks **1**,[9] **3**,[10] **4**,[10] **5**[10], **6a**[12] and **6b**.[12] Thus, conversion of the phenylthioglycoside **1** to fluoride **2** with NBS–DAST (CH_2Cl_2, 0–25 °C, 85%) followed by coupling with **3** ($AgClO_4$, $SnCl_2$, 4-Å MS, CH_2Cl_2, −15–0 °C) led to the

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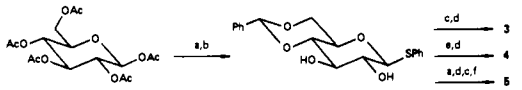
(9) Cellobiose derivative **1** was prepared from D-(+)-cellobiose peracetate by treatment with PhSH (1.2 equiv) in the presence of $SnCl_4$ (0.3 equiv) (PhH, 60 °C) in 82% yield.

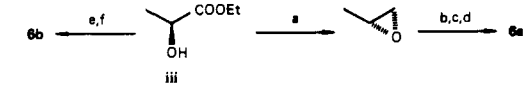
(10) Compounds **3**–**5** were prepared from D-(+)-glucose pentaacetate (i)



via intermediate ii as follows: (a) 1.2 equiv of PhSH, 0.7 equiv of $SnCl_4$, PhH, 60 °C, then 1.0 equiv of NaOMe, MeOH, 25 °C, 85%; (b) 3.0 equiv of $PhCH(OMe)_2$, 0.05 equiv of CSA, PhH, 25 °C, 90%; (c) 2.5 equiv of Ac_2O, 2.0 equiv of DMAP, CH_2Cl_2, 0–25 °C, 95%; (d) (i) excess $NaCNBH_3$,[11] 4-Å MS, THF, 25 °C, 92%; (ii) HCl(g), Et_2O; (e) 6.0 equiv of NaH, 4.0 equiv of $PhCH_2Br$, THF, Δ, 90%; (f) 1.5 equiv of NBS, 1.3 equiv of DAST, CH_2Cl_2, -15 °C, 85%.

(11) Garegg, P. J.; Hultberg, H.; Wallin, S. *Carbohydr. Res.* **1982**, *108*, 97.

(12) Compounds **6a** and **6b** were synthesized from L-(+)-ethyl lactate (iii)



as follows: (a)[13] TsCl–pyr, then BH_3–THF, then 50% NaOH, 40% overall; (b) NaH–$PhCH_2OH$ (5.0 equiv of each) THF, 50 °C, 65%; (c) 1.1 equiv of Ph_2-*t*-BuSiCl, 1.1 equiv of imidazole, DMF, 25 °C, 95%; (d) H_2, Pd/C, EtOH, 25 °C, 90%; (e) 1.4 equiv of Ph_2-*t*-BuSiCl, 2.6 equiv of Et_3N, 0.1 equiv of DMAP, CH_2Cl_2, 25 °C; (f) 2.0 equiv of BH_3, THF, 25 °C, 92%.

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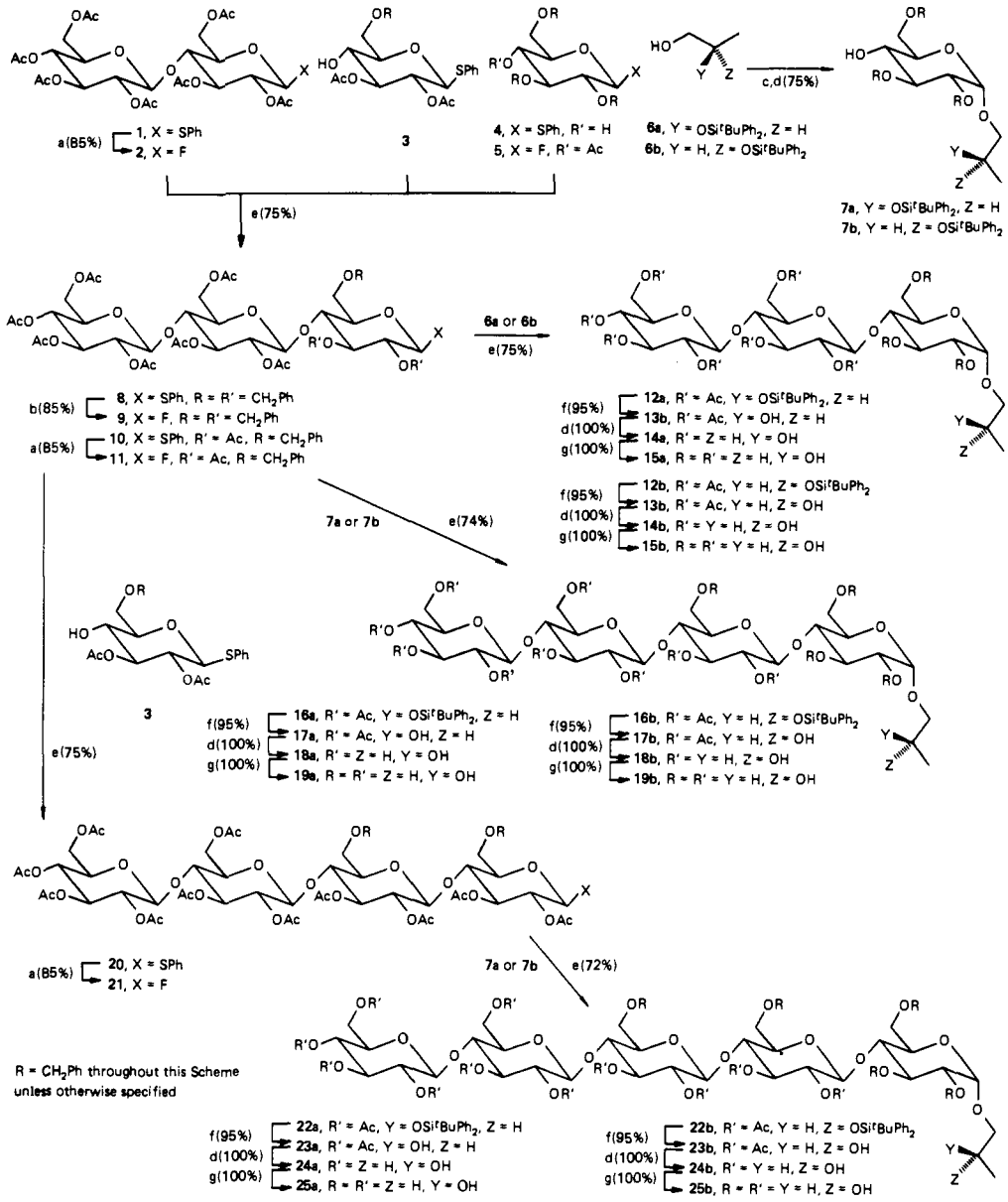
Scheme I.[a] Synthesis of Rhynchosporosides



[a] (a) 1.3 equiv of DAST, 1.5 equiv of NBS, CH_2Cl_2, 0–25 °C, 1.5 h; (b) 1.3 equiv of DAST, 1.5 equiv of NBS, CH_2Cl_2, −15 °C, 1 h; (c) 1.8 equiv of $SnCl_2$, 1.8 equiv of $AgClO_4$, 4-Å MS, Et_2O, −15 °C, 18 h; (d) (i) 1.0 equiv of NaOMe, MeOH, 25 °C, 8 h; (ii) H^+-Amberlyst-15; (e) 1.8 equiv of $SnCl_2$, 1.8 equiv of $AgClO_4$, 4-Å MS, CH_2Cl_2, −15 °C, 18 h; (f) excess HF·pyr, THF, 0–25 °C, 4 h; (g) H_2, $Pd(OH)_2$–C, MeOH, 25 °C, 14 h.

new phenylthio glycoside **8** (75%).[5] Activation of **8** with NBS–DAST at −15 °C to fluoride **9** (85%) and coupling with the propanediol derivative **6a** or **6b** ($AgClO_4$, $SnCl_2$, 4-Å MS, Et_2O, −15 °C) furnished [3*R*]- or [3*S*]-rhynchosporoside derivative **12a** or **12b** (75%), respectively. Sequential desilylation (excess HF·pyr, 95%), deacetylation (NaOMe, MeOH, 25 °C, 100%), and debenzylation ($Pd(OH)_2$–C, EtOH, 25 °C, 100%) finally led to [3*R*]- and [3*S*]-rhynchosporosides **15a** and **15b** in excellent overall yields.

For the tetrasaccharide and pentasaccharide series, building blocks **7a** and **7b** were first constructed as follows. Glycosyl fluoride **5** was coupled to 1,2-propanediol derivatives **6a** and **6b** under the conditions for α-glycosidation and the exclusively obtained α-glycosides were deacetylated under the standard conditions leading to the requisite **7a** and **7b**, respectively, in 75% overall yield. The other desired fragment, trisaccharide fluoride **11**, was prepared from **2** and **3** via **10** (85%) by employing β-glycosidation conditions (75% yield). Coupling of **11** with **7a** and **7b** as described above for **15a** and **15b** (74%) followed by deprotection furnished [4*R*]- and [4*S*]-rhynchosporosides **19a** and **19b** stereospecifically and in similarly high yields.

Finally, coupling of trisaccharide fluoride **11** with thio sugar **3** (75%) followed by conversion of the resulting phenylthio tetrasaccharide **20** to its glycosyl fluoride **21** (85%) and coupling with **7a** and **7b** furnished (72%), after the necessary deprotections, [5*R*]- and [5*S*]-rhynchosporosides **25a** and **25b**, again with complete stereospecificity and in high overall yield. All rhynchosporosides were obtained as colorless, amorphous solids soluble in water but sparingly soluble in common organic solvents.

The stereochemistry of the anomeric centers and high purity of the synthesized compounds was established by modern high-resolution ^1H and ^{13}C NMR techniques. Thus, the ^1H NMR spectra of all rhynchosporosides and their derivatives generally exhibited a sharp doublet at δ 4.92 (J = 3.7 Hz) for the proton associated with the α-linkage and the requisite number of doublets around δ 4.53–4.50 (J = ~7.5Hz) for the protons corresponding to the β-linkages. Furthermore, the ^{13}C NMR spectra of the peracetylated derivative exhibited the diagnostic signal for the α-bond (~δ 95.5) and the requisite number of characteristic signals for the β-bonds (~δ 100.5).[14] In Figure 1 the essentials

for these crucial experiments are exhibited for the specific case of the peracetate of [4S]-rhynchosporoside (**19b**). Thus in plot A (Figure 1) (^{1}H decoupled ^{13}C NMR spectrum) the anomeric signals are located at δ 100.79, 100.66, and 100.50 for the β-bonded carbons and at δ 95.53 for the α-bonded carbon. Plot B (Figure 1) (2D ^{1}H-^{13}C heteronuclear chemical shift correlated spectrum)[15] correlates the chemical shifts of the anomeric carbons with the respective anomeric protons which assisted in their assignment. These experiments provided a convenient and unambiguous way of establishing the stereochemical configuration of the rhynchosporosides, their high purity and the specificity of the reported coupling reactions.

With these rhynchosporosides now readily available in pure form by synthesis, their isolation from nature, structural elucidation, and biological evaluation becomes feasible. Preliminary bioassays with the tri-, tetra-, and pentasaccharides, for example, indicated high destructive potency for the [3*R*]-, [4*R*]-, and [5*R*]-rhynchosporosides **15a**, **19a**, and **25a** which caused massive tip wilt and necrosis in young barley plants.[16,17]

Acknowledgment. We express our many thanks to Professors G. A. Strobel and P. Auriol for helpful discussions and biological investigations. We are also indebted to Dr. Manfred Spraul of Bruker Analytische Messtechnik GMBH, West Germany, for assistance in obtaining the high-field NMR data and John Dykins of this department for his mass spectroscopic assistance. This work was financially supported by Merck Sharp & Dohme, the Camille and Henry Dreyfus Foundation, and the National Institutes of Health.

Supplementary Material Available: Spectral and analytical data and structures for compounds **15a**, **15b**, **19a**, **19b**, **25a**, and **25b** (3 pages). Ordering information is given on any current masthead page.

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(17) All new compounds exhibited satisfactory spectroscopic and analytical and/or exact mass data. Yields refer to spectroscopically and chromatographically homogeneous materials.

Adsorption and Decomposition of Formaldehyde on the Ru(001) Surface: The Spectroscopic Identification of η^2-H_2CO and η^5-HCO

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Received May 6, 1985

The interaction of formaldehyde with transition-metal surfaces is of obvious importance in view of the fact that species such as M-CH_2O and M-CHO may play a key role in the catalytic hydrogenation of carbon monoxide.[1-3] Recently, several organometallic complexes have been identified in which both formaldehyde[4-7] and the formyl group[8] function as dihapto (η^2-) ligands. In this paper, we report the results of high-resolution electron energy loss (HREELS) measurements of formaldehyde adsorbed on the hexagonally close-packed Ru(001) surface that demonstrate the existence of both η^2-H_2CO and η^2-HCO. This represents the first spectroscopic identification of either species on any metal surface.

Table I. Mode Assignments for η^2-H_2CO (η^2-D_2CO) on Ru(001)

mode	η^2-H_2CO, cm^{-1}	η^2-D_2CO, cm^{-1}	frequency ratio (H_2CO/D_2CO)
ν(CO)	980	1020	0.96
ν_a,ν_s(CH_2)	2940	2225	1.32
δ(CH_2)	1450	1190	1.22
ω(CH_2)	1160	865	1.34
ρ(CH_2)	840	620	1.35

Table II. Mode Assignments for η^2-HCO (η^2-DCO) on Ru(001) with Corresponding Assignments from the Model Compound $HCOOCH_3$ ($DCOOCH_3$) (See Ref 15)

mode	η^2-HCO, cm^{-1}	$HCOOCH_3$, cm^{-1}	η^2-DCO, cm^{-1}	$DCOOCH_3$, cm^{-1}
ν(CH)	2900	2943	*a*	2216
δ(CH)	1400	1371	980	1048
ν(CO)	1180	1207	1160	1213
π(CH)	1065	1032	825	870
ν(Ru-HCO)	590		550	

[a] Weak and not resolved from the tail of the strong feature due to adsorbed CO at 1990 cm^{-1}.

The ultrahigh vacuum (UHV) system in which the experiments were performed has been described previously.[9] HREELS was used to identify surface reaction products after adsorption at 80 K, subsequent annealing up to 600 K, and recooling to 80 K to record the spectra. Gaseous H_2CO and D_2CO were produced by thermal dehydration and depolymerization of their parent polyoxymethylene glycols (paraformaldehyde) and were introduced into the UHV chamber through a leak valve. The H_2CO (D_2CO) produced by this method contains 3-5% H_2O (D_2O) impurity,[10] and, consequently, spectra recorded after heating below 170 K are expected to show vibrational features attributable to small amounts of coadsorbed water.[11]

Exposing the Ru(001) surface at 80 K to 7 langmuirs (1 langmuir = 10^{-6} torr s) or more of H_2CO or D_2CO results in the formation of molecular multilayers of formaldehyde, as evidenced by a comparison of the observed vibrational spectra to the IR spectrum of gaseous formaldehyde.[12] Annealing the surface to 140 K desorbs the multilayer, leaving adsorbed carbon monoxide (θ = 0.20 CO molecules/Ru surface atom),[13] hydrogen adatoms (θ = 0.40),[14] and another surface species (θ = 0.10) which is stable to approximately 250 K. This new species is identified as η^2-formaldehyde. The spectra for H_2CO and D_2CO are shown at the top of Figure 1, and mode assignments are given in Table I. The observed CO stretching frequency of approximately 1000 cm^{-1} is consistent with a reduction in bond order of the CO bond from double to single and is in good agreement with the CO stretching frequency of 1017 cm^{-1} for η^5-H_2CO in the organometallic compound $(PPh_3)_2(CO)_2Os(\eta^2$-$H_2CO)$.[4] The observed frequencies and deuteration shifts for the various CH_2 modes agree well with those observed for sp^3-CH_2 groups in various molecules.[15]

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