°C. The synthetic angelicin had an R_f value and ^1H and ^{13}C NMR spectra identical with those of a natural sample kindly provided by Professor Berenbaum. A mixed melting point was found to be within 0.5 °C of the individual samples.

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Total Synthesis of Octosyl Acid A. Intramolecular Williamson Reaction via a Cyclic Stannylene Derivative

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Abstract: The total synthesis of the title compound has been achieved. The key features involved (i) the construction of a carbon-linked furanoside–pyranoside by a cyclocondensation reaction of compound **8**, (ii) the use of the pyran matrix to elaborate the required stereochemistry at carbon 7′ of a nucleoside (see compound **34**), and (iii) cyclization via a 2′,3′-stannylene derivative (see transformation **35** to **36**).

Background and Synthetic Plan. One of the primary concerns of our laboratory since 1984 has been the development of totally synthetic routes to a class of compounds known as complex or "higher" monosaccharides (**1**). Elsewhere, we have catalogued this interesting group of saccharides and summarized some of the salient points of interest concerning their biological activity.[1] In this presentation, we provide a full account of the synthesis of a member of this family, i.e., octosyl acid A.[2a-c]

The octosyl acids were isolated from *Streptomyces cacaoi*.[3] They are part of a broader group of polyoxin antifungal nucleosides.[4] It was the novel chemical structures of the octosyl acids that first engaged our attentions. A key element of our proposal for a synthesis involved the challenge of chirality extension from carbohydrate matrices.[5] Moreover, the novel biological profile of a congener of octosyl acid A (**1**) (Figure 1), namely, the modified nucleoside **2**, served to augment interest in achieving synthetic progress in the area. Semisynthetic **2** inhibits the action of cyclic AMP phosphodiesterases from a variety of animal tissues. It is possible that the phosphodiesterase enzyme recognizes compound **2** as a "carba" version of 3′,5′-cyclic nucleotides [cf. cyclic AMP, (**3**)].[6a-c]

Our approach called for the use of the aldehyde **5**, derivable from ribose,[7] as our starting material. A total synthesis of racemic **5** from a sequence that started with formaldehyde and diene **4** has been achieved.[8a,b] This demonstration sufficed to establish *in principle* a fully synthetic route to goal systems derived from **5**. As a practical matter, the material derived from naturally occurring D-ribose served as our starting material.

The strategy called for elongation of **5** to reach, eventually, a system of the type **6** (Figure 2). Examination of conformer **6c** (c = chair) suggests the possibility of displacement of the OL (leaving) from $C_{7'}$ by some nucleophilic version of a $C_{3'}$ hydroxyl function. Of course, in our plan inversion of configuration at $C_{7'}$ was anticipated. Accordingly, access to the $C_{5'}$(R), $C_{7'}$(R) diastereomer would be necessary.

While suggestive of the possibilities for establishing the trans-fused pyranofuran system, conformational figure **6c** shows that *for cyclization through a chairlike transition state to occur, the OL (leaving) and OP (protected alcohol) functions at $C_{7'}$ and $C_{5'}$ respectively, must be in a pre-1,3-diaxial state.* There was little in the way of precedent to deal with the feasibility of such a reaction.

Continuing in the retrosynthetic vein, it was presumed that reduction of the keto group of the dihydropyrone moiety in compound **7** would afford the equatorial alcohol shown in **8**. Excision of C_1 fragment (carbon 9′) from the system with appropriate functional group management might then lead to the required series **6**.

Given this recognition, a viable strategy presented itself. Compound **7** could itself be synthesized in one step from a Lewis acid catalyzed cyclocondensation reaction of diene **4a** with aldehyde **5**. Crucial to the success of the enterprise was the facial control that would be exerted by aldehyde **5** in such a cyclocondensation process.

It was hoped that the reactive conformer of **5** would be the one depicted. Elsewhere[9,10] we have reported that this is in fact the case and that cyclocondensation of this aldehyde with dienes **4a** or **4b** under Lewis acid catalysis occurs in the indicated α sense (i.e., anti to the ribosyl framework) with high stereoselectivity. This type of reaction, which provides a route to carbon-linked disaccharides, was extremely useful in providing access to the higher monosaccharides.

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‡ Yale Chemical Instrumentation Center.

(1) Danishefsky, S.; DeNinno, M. P. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 15.
(2) (a) For a preliminary account of a portion of this work, see: Danishefsky, S.; Hungate, R. *J. Am. Chem. Soc.* **1986**, *108*, 2486. (b) For the only other synthesis of octosyl acid, which appeared concurrently with our submission, see: Hanessian, S.; Kloss, J.; Sugawara, T. *Ibid.* **1986**, *108*, 2758.
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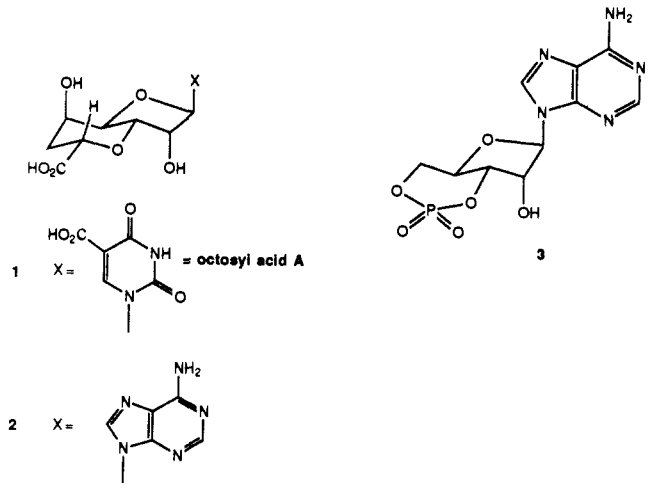
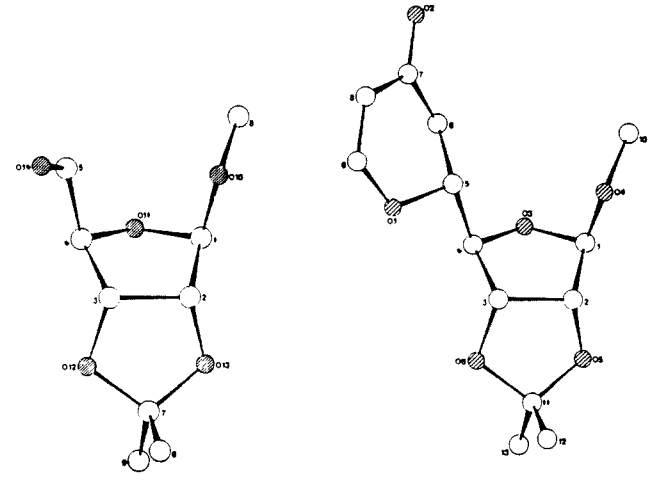


Figure 1.

Of course, the success of a reaction does not per se ensure the correctness of the arguments that went into its proposition. In connecting stereochemical prediction with outcome, it is often the case that an even number of incongruencies between perception and reality might be overlooked because the final measurable outcome can well be the same. For instance, in the type of problem before us, the prediction in going from compound **5** to compound **7** rests on a conformational assumption and an assumption as to the diastereofacial sense of attack on the Curtin–Hammett conformer.[11] The measurable outcome does not per se distinguish between the cases where both suppositions are either "right" or "wrong". In seeking further insight into this matter, an X-ray crystal structure of compound **5** was obtained. An ORTEP drawing



ORTEP drawing of **5**[12] ORTEP drawing of **7**[13]

of this substance is shown.[12] While fully mindful of the limitations imposed by the Curtin–Hammett principle[11] in attempting to connect reacting conformers with ground states, it is at least reassuring when the ground-state stereochemistry is known with confidence.

Results

(i) The C_7–C_8 Oxido Route. Dihydropyrone **7** was obtained in 85% yield under previously described conditions.[9,10] An X-ray crystal structure of this compound served to rigorously establish its stereochemistry. Parenthetically we note the near anti relationship of the furanosidal and pyranosidal oxygen atoms (dihedral angle for $O_3C_4C_5O$ = 170.5°; see ORTEP drawing) in compound **7**.[12] This anti juxtaposition could well arise from its minimization of dipolar repulsions. Luche type reduction[13] ($NaBH_4$·$CeCl_3$) led to the C_7 equatorial alcohol depicted in compound **8**. Spectroscopic and TLC analysis of the crude reaction mixture at this stage pointed toward the possibility that ca. 10% of the epimeric C_7· axial alcohol might be present. Anticipating the need for protecting groups that would eventually be differentiable, compound **8** was converted (sodium hydride–*p*-methoxybenzyl chloride) to its C_7· *p*-methoxybenzyl ether **9** (90% yield). The stage was set to disconnect the pyran structure so that the acyclic side chain could be generated.

The specific goal substrate in this phase of the investigation was compound **22**. It was felt that the epoxide would manifest its electrophilicity at C_7·. The oxido linkage was seen to provide a convenient form of storage for the eventual C_8· carboxy functionality. The lessons accumulated in this foray, albeit unsuccessful, were instructive in developing what became the successful route. Reaction of compound **9** with osmium tetroxide (catalytic) and sodium metaperiodate was followed by treatment of the C_8· aldehyde C_5· formyloxy product with potassium carbonate in methanol (Figure 3). The C_5· alcohol thus generated, cyclized onto the C_8 aldehyde producing the hemiacetal **10**. The latter was opened in a reductive fashion (sodium borohydride) producing diol **11** (86% from **9**). An elaborate series of maneuvers was necessary to convert compound **11** to the required epoxide **22**. The primary alcohol of **11** was selectively protected according to Hanessian[14] affording **12** which, upon benzylation, gave **13** (90% from **10**). At this stage, both the PMB and silyl protecting groups were removed[15] giving rise to diol **14** (93% from **12**). The acetonide function was cleaved through the action of methanolic HCl to provide compound **15** (mixture of anomers). Perbenzoylation afforded the tetrabenzoate **16** with a uniquely differentiated benzyl ether at C_5·. The methyl glycoside was transformed to anomeric acetates **17** (70% from **13**).

A Vorbruggen reaction of **17** with 2,4-bis[(trimethylsilyl)-oxy]-5-carbomethoxypyrimidine (**18**)[16a] in the presence of bis(trimethylsilyl triflate)[17] gave rise to the nucleoside (78%), which was converted to its *N*-benzyl derivative **19** (82%). The stereochemistry at C_1· was assigned by analogy with previous work, wherein it is assumed that there is inversion of configuration in the opening benzyloxonium ion by the bis(silylimidate) nucleophile.

Perdebenzoylation gave rise to a tetraol **20** which was converted in low yield to its monotosylate through the action of pyridine and tosyl chloride. Reaction of **21** with potassium *tert*-butoxide gave the diol epoxide **22** (86% from **21**).

A variety of attempted base-induced reactions carried out on epoxide **22** failed to produce recognizable internal alkylation products. Extensive decomposition was the main result. The use of Lewis acids was examined. It was reasoned that such conditions might allow for cyclization under milder conditions. In the event, reaction of **22** with BF_3 etherate in methylene chloride at −78 °C for 1 h did indeed lead to cyclization. After acetylation, two products could be separated on HPLC. While the products were not fully characterized, examination of their NMR spectra sufficed to reveal that the major one (ca. 3:1) was the one with the furano perhydrofuranooxapene system, shown in **23**. The minor product was formulated as **24**, which contains the pyranofuran substructure needed for a synthesis of octosyl acid A. It should be emphasized that its stereochemical assignment rests on the reasonable but unproven proposition of inversion of configuration in the cyclization step.

A variety of attempts to tilt the ratio of **24** to **23** in the desired direction were unsuccessful. Since the overall yield of formation of epoxide **22** from diol **20** was low (due to the inefficient monotosylation step), and since the major cyclization product was the one arising from apparent 7-endo closure,[18] this route was

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(12) The protocols for the crystallography on compounds **5** and **6** are found in the supplementary material, together with the data.
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(16) Commercially available from Aldrich.
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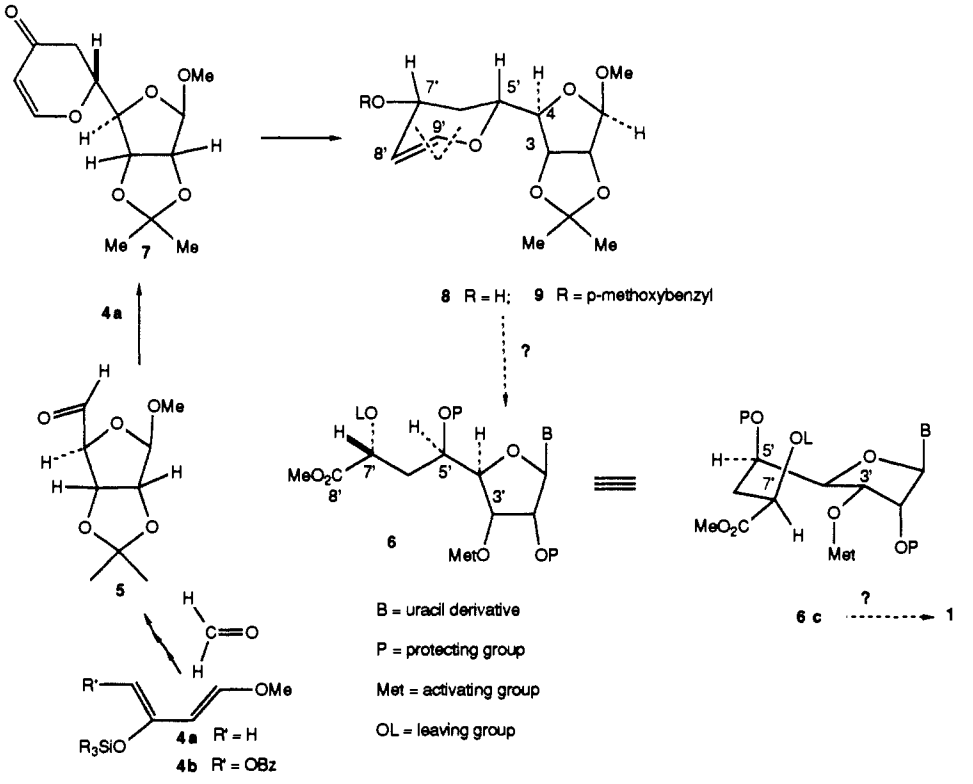

Figure 2.

abandoned. While this initiative led to an unexpected and disappointing result, it did point toward the need for a cyclization substrate that is not complicated by additional rigidities such as are found in an oxido linkage.

Since the oxido electrophile **22** had cyclized principally at $C_{8'}$, we investigated the possibilities of a system such as **26** (Figure 4), bearing a substituted lactate electrophile. As was the case with the 7,8-oxido proposition, the lactate proposal was beset with its own a priori uncertainties. Not the least of these concerns involved the introduction and maintenance of the diverse functionality present in such an ensemble. For example, it seemed unlikely that an undifferentiated triol precursor such as **25** (L = P = P' = H) would be satisfactory since this would require specific activation of the $C_{7'}$ hydroxyl group in the presence of alcohols at $C_{2'}$ and $C_{3'}$. If the oxygen at $C_{7'}$ were activated (OL, leaving group) before the hydroxyl groups at $C_{2'}$ and $C_{3'}$ were "freed", the question of the stability of "OL" to the deprotection of P (and P') was of some concern. Moreover, the proper timing for introducing the carboxyuracil function at $C_{1'}$ had to be arranged. Finally, there were uncertainties as to whether **26** would in practice function as an internal alkylating agent (via the $C_{7'}$ leaving group) or as an internal acylating agent via the $C_{8'}$ ester group.

To investigate these and related questions, we returned to hemiacetal **10**, an intermediate in the 7',8'-oxido route. Oxidation of this substance with silver carbonate on Celite afforded lactone **27** (Figure 5).[19] Upon opening of the lactone ring (aqueous lithium hydroxide), the secondary alcohol exposed at $C_{5'}$ could be benzylated through the action of sodium hydride–benzyl bromide. The resultant $C_{5'}$ benzyloxy acid was converted (diazomethane) to methyl ester **28**. The *p*-methoxybenzyl function at $C_{7'}$ was oxidatively cleaved,[16] generating hydroxy ester **29**. Mesylation of the unique hydroxyl at C_7 gave rise to the "lactate mesylate" **30**.

*We were pleased to find that the mesylate we proposed to employ as our leaving group (see OL in structure **26**) also served to protect the $C_{7'}$ hydroxyl through a remarkable series of steps.* When compound **30** was subjected to acidic hydrolysis (aqueous methanolic HCl) followed by acylation, first with pyridine acetic anhydride and then with acetic anhydride in acetic acid–sulfuric acid, a 3:1 mixture of ribosyl acetate anomers was obtained in ca. 75% yield. For purposes of characterization, the components were separated by silica gel chromatography affording acetates **31** (major) and **32** (minor). For synthetic purposes the mixture was subjected to a Vorbruggen type reaction[17b] with compound **18**[17a] under the influence of trimethylsilyl triflate. There was thus obtained a 90% yield of nucleoside **33**. Deacylation of **33** with sodium methoxide–methanol did indeed provide the critical diol monomesylate **34**. A version of the projected compound **25** was thus reached. The mesylate function that was appended to the unique $C_{7'}$ alcohol at the stage of compound **29** had survived the transformations leading from **30** to **34**. The final demand that we placed on this function was that it be displaced by the $C_{3'}$ alcohol, hopefully without explicit differentiation of $C_{2'}$ and $C_{3'}$. Unfortunately, several attempts to accomplish the transformation under basic (Williamson type) conditions were extremely discouraging. In keeping with the remarkable instinct for survival manifested by the α-mesyloxy ester, a variety of mildly basic reaction conditions led to recovery of compound **34**. Under more forcing conditions, extensive decomposition ensued, and no identifiable products were isolated.

The possibility was recognized that a cyclic stannylene derivative of **25** might be employed to advantage.[20] It was hoped that such a derivative would serve to activate the 3'-hydroxyl while, in effect, protecting the $C_{2'}$ alcohol. Moreover, the essentially neutral character of a stannylene might prove more amenable to higher temperatures than could be employed with metal alkoxide combinations.

In the event, compound **34** reacted with $(Bu_3Sn)_2O$ in methanol. Such a treatment was expected to afford a derivative of the type **35**. When this presumed intermediate was subjected to the action of CsF in DMF at 60 °C, a new product emerged (Figure 6). This compound, isolated in 77% yield had the spectral and analytical properties expected of the desired cyclization product **36**. Hydrogenolysis of this substance with $Pd(OH)_2$[21] afforded octosyl

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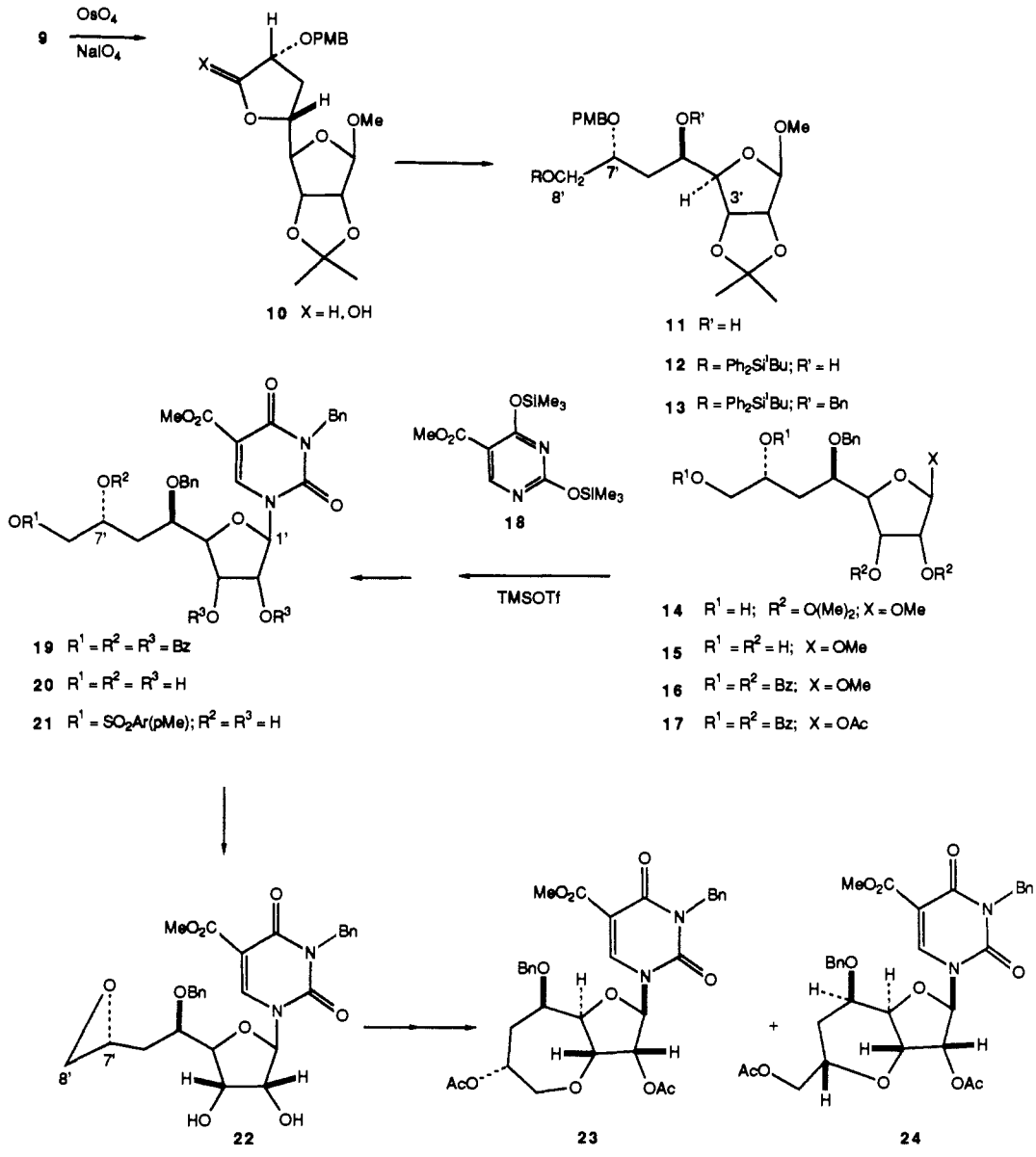


Figure 3.

acid A dimethyl ester **37**. A search of spectral and chromatographic comparisons of fully synthetic **37** showed it to be identical with the compound prepared by esterification of authentic octosyl acid with methanolic HCl.

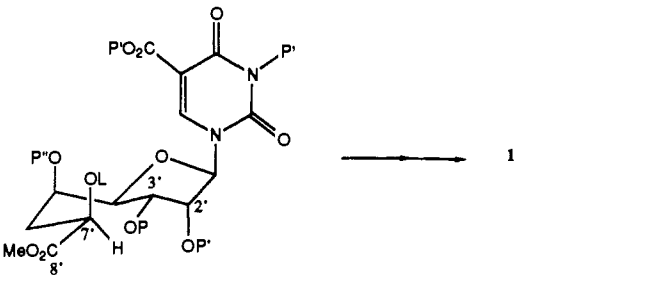
Finally, hydrolysis of fully synthetic **37** with lithium hydroxide in aqueous THF afforded synthetic octosyl acid, by spectral comparison identical with an authentic sample obtained from Professor Isono. Very shortly after conclusion of this effort another total synthesis of **1** was accomplished by Professor Hanessian and co-workers.[2b] The optical rotation of our fully synthetic **1** $[\alpha]^{23}_D$ +9.1° (*c* 0.8 N NaOH) agreed very closely with that reported by this group. The total synthesis of octosyl acid A was thus accomplished.

Experimental Section

Methyl 5,9-Anhydro-6,8-dideoxy-2,3-*O*-(1-methylethylidene)-β-D-*allo*-non-8-enofuranosid-7-ulose (7). Aldehyde **5** (1.15 g, 5.4 mmol) and diene **4a** (1.1 g, 6.2 mmol) were dissolved in THF (45 mL) and cooled to 0 °C. Zinc chloride (0.71 g, 5.6 mmol, freshly fused) was added. The ice bath was removed and the reaction stirred at room temperature for 9 h. The reaction was poured into saturated aqueous $NaHCO_3$ and extracted with CH_2Cl_2 (3 × 50 mL). The organic phases were combined, washed with H_2O followed by saturated NaCl, and dried over Na_2SO_4. The crude material was concentrated to ca. 25 mL, exposed to trifluoroacetic acid (1 equiv), and allowed to stand at room temperature for 3 h. The reaction mixture was diluted with EtOAc (100 mL) and washed with saturated aqueous $NaHCO_3$ (2 × 50 mL) and brine and dried over Na_2SO_4. The solution was concentrated in vacuo and the orange oil crystallized with Et_2O–hexane to yield 0.75 g of compound **7**. The mother liquor was concentrated and further purified via flash chromatography (30% ethyl acetate–hexane) to give an additional 0.60 g of product, total 1.35 g (89%). Recrystallization from Et_2O–hexane provided an analytical sample as well as crystals suitable for X-ray analysis (see text): mp 70–71 °C; ^1H NMR (490 MHz) δ 1.33 (s, 3 H), 1.49 (s, 3 H), 2.65 (m, 2 H), 3.33 (s, 3 H), 4.25 (d, 1 H, *J* = 10.7 Hz), 4.33 (m, 1 H), 4.59 (d, 1 H, *J* = 5.9 Hz), 4.89 (d, 1 H, *J* = 5.8 Hz), 4.99 (s, 1 H), 5.43 (dd, 1 H, *J* = 6.04, 0.7 Hz), 7.33 (d, 1 H, *J* = 6.0 Hz); $[\alpha]^{25}_D$ −83.7° (*c* 1.91, $CHCl_3$).

Methyl 5,9-Anhydro-6,8-dideoxy-7-*O*-[(4-methoxyphenyl)methyl]-2,3-*O*-(1-methylethylidene)-L-*glycero*-β-D-*allo*-non-8-enofuranoside (9). Pyrone **7** (10.4 g, 37.2 mmol) and $CeCl_3 \cdot 7H_2O$ (13.9 g, 37.3 mmol) was dissolved in methanol (300 mL) and cooled to −78 °C. $NaBH_4$ (1.4 g, 36.8 mmol) was added over 1 h with the aid of a solid addition funnel (Lab Glass Inc.), and the heterogeneous reaction was stirred an additional 1 h. Excess $NaBH_4$ was slowly destroyed with 1 N HCl until the pH registered at ca. 5. Methanol was removed in vacuo and the residue partitioned between EtOAc–H_2O. The organic layer was dried, (Na_2SO_4), and the volatiles were evaporated. Without purification the crude allylic alcohol **8** (11.5 g) was dissolved in DMF (100 mL) and cooled to 0 °C, and *p*-methoxybenzyl chloride (7.6 g, 48.6 mmol) was added. NaH

(21) Pearlman, W. M. *Tetrahedron Lett.* **1967**, *10*, 1663. In this system, debenzylation was accompanied by hydrogenation of the heterocyclic ring. This can be minimized by employing a large excess (300% by weight) of catalyst and short reaction times.



25 L = P = P' = H; P' = protecting group

26 OL = leaving group; P = H; P' = H or protecting group; P' = protecting group

Figure 4.

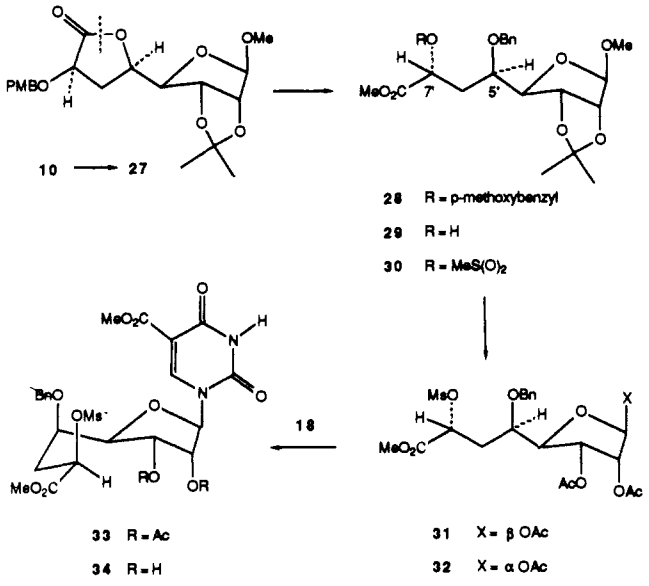


Figure 5.

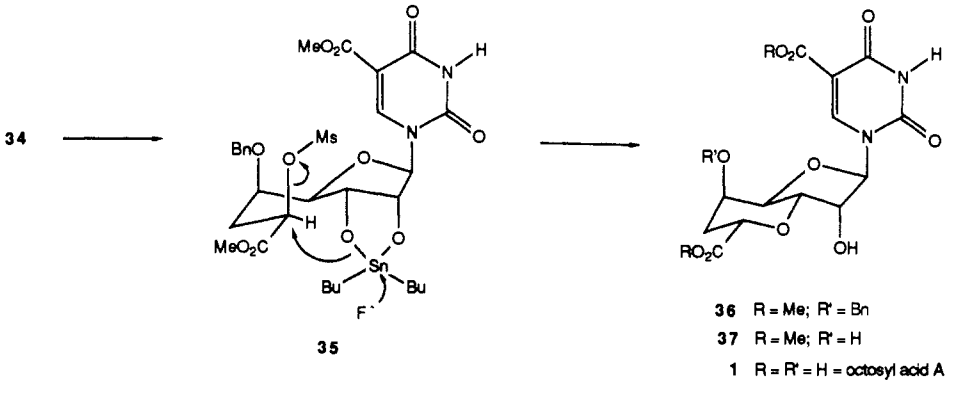
(50% dispersion in mineral oil, 2.5 g, 52 mmol) was then added and the reaction allowed to stir overnight with the ice bath being allowed to slowly warm to room temperature. Excess NaH was carefully destroyed with H_2O, and the contents of the flask were poured into H_2O (50 mL). The aqueous phase was extracted with Et_2O (3 × 100 mL). The organic layers were combined and washed with saturated aqueous $NaHCO_3$, H_2O, and finally with saturated NaCl. The solution was dried, (Na_2SO_4) and concentrated in vacuo, leaving a residue which was purified via flash liquid chromatography (LC) (15% ethyl acetate–hexane) to give 13.5 g (90%) of the title compound as a pale yellow oil: R_f 0.29; $[\alpha]^{23}_D$ +15.1° (*c* 3.89, $CHCl_3$); ^1H NMR (500 MHz) δ 1.33 (s, 3 H), 1.50 (s, 3 H), 1.83 (dt, 1 H, *J* = 9.8, 0.4 Hz), 2.37 (m, 1 H), 3.3 (s, 3 H), 3.80 (s, 3 H), 3.84 (dt, 1 H, *J* = 10, 2.5 Hz), 4.15 (br t, 1 H), 4.21 (d, 1 H, *J* = 10.1 Hz), 4.52 (dd, 2 H, *J* = 16.2, 11.4 Hz), 4.58 (d, 1 H, *J* = 6.5 Hz), 4.90 (m, 2 H, 4.97 (s, 1 H), 6.39 (d, 1 H, *J* = 1 Hz), 6.89 (d, 2 H, *J* = 8.6 Hz), 7.28 (d, 2 H, 8.5 Hz); IR ($CHCl_3$) 3020, 2940, 1648, 1615, 1525 cm^{-1}; MS, *m/e* 392 (M^+), 377, 360, 224, 209, 150, 133, 121 (100); calcd for $C_{21}H_{28}O_7$ 392.1835, found 392.1822.

(Methyl 6-deoxy-7-*O*-[(4-methoxyphenyl)methyl]-2,3-*O*-(1-methylethylidene)-L-*glycero*-β-D-*allo*-octofuranosid)uronic Acid α-Lactone (27). Dihydropyran **9** (9.2 g, 23 mmol) was dissolved in dioxane–H_2O, 4:1 (1.25 L). $NaIO_4$ (25 g, 115 mmol) was added followed by OsO_4 (58 mg, 0.23 mmol), and the reaction was allowed to proceed overnight at room temperature. The reaction mixture was filtered, and concentrated in vacuo. The dark residue was taken up in MeOH (100 mL) and stirred at room temperature in the presence of 5% aqueous K_2CO_3 (2 mL) for 1 h. The MeOH was evaporated and the residue taken up in Et_2O (250 mL), washed with saturated aqueous NaCl, and dried Na_2SO_4. Flash LC with 20% ethyl acetate–hexane gave 8.5 g (93%) of lactol **10** as a colorless oil. The ^1H NMR (500 MHz) and IR ($CHCl_3$) spectra indicated this material to exist mainly as an anomeric mixture of lactols: ^1H NMR (500 MHz) δ 5.28 (dd, 1 H, *J* = 2.9, 3.3 Hz), 5.46 (d, 1 H, *J* = 3 Hz), 9.80 (s, 1 H); IR ($CHCl_3$) 3600, 3450, 1732 cm^{-1}; MS, *m/e* 396 (M^+).

The lactol mixture **10** (4.2 g, 10.4 mmol) was dissolved in xylene and Ag_2CO_3–Celite (15 g, 1 mmol, 0.57 g) added. The reaction was refluxed for 1.5 h, cooled, and filtered through Florasil. The product was purified by flash LC (30% ethyl acetate–hexane) to yield 3.58 g (86%) of lactone **27** as a colorless oil: R_f 0.24; $[\alpha]^{23}_D$ +2.8° (*c* = 13.8, $CHCl_3$); ^1H NMR (490 MHz, $CDCl_3$) δ 1.31 (s, 3 H), 1.47 (s, 3 H), 2.18 (dt, 1 H, *J* = 13.4, 8.1 Hz), 2.54 (m, 1 H), 3.32 (s, 3 H), 3.81 (s, 3 H), 4.15 (d, 1 H, *J* = 9.9 Hz), 4.19 (t, 1 H, *J* = 8.3 Hz), 4.26 (m, 1 H), 4.59 (d, 1 H, *J* = 6.0 Hz), 4.68 (d, 1 H, *J* = 11.6 Hz), 4.85 (d, 1 H, *J* = 9.3 Hz), 4.91 (d, 1 H, *J* = 12.6 Hz), 4.95 (s, 1 H), 6.89 (d, 2 H, *J* = 8.6 Hz), 7.31 (d, 2 H, *J* = 8.5 Hz); IR ($CHCl_3$) 1780 cm^{-1}; MS, *m/e* 394 (M^+), 379, 236, 211, 137 (100); calcd for $C_{20}H_{26}O_8$ 394.1627, found 394.1614.

Methyl (Methyl 6-deoxy-7-*O*-[(4-methoxyphenyl)methyl]-2,3-*O*-(1-methylethylidene)-5-*O*-(phenylmethyl)-L-*glycero*-β-D-*allo*-octofuranosid)uronate (28). Lactone **27** (3.5 g, 8.6 mmol) was dissolved in dimethoxyethane (21 mL) and H_2O (2 mL). Lithium hydroxide monohydrate (0.370 g, 19 mmol) was added and the reaction mixture heated to 50 °C for 2 h, at which time TLC indicated no starting material to be present. The volatiles were evaporated. Most of the water was removed by azeotropic distillation of the residue azetroped with toluene. The residue was further dried at 50 °C for 4 h. To the salt, so prepared, were added DMF (22 mL), benzyl bromide (7.3 g, 43 mmol), and NaH (2.2 g, 45 mmol, 50% dispersion in mineral oil), and the reaction was allowed to proceed at room temperature overnight. Excess NaH was destroyed by cautious addition of H_2O followed by removal of volatiles in vacuo. The residue was triturated with Et_2O (3 × 10 mL) followed by 1 N HCl (pH 2). The aqueous layer was extracted with EtOAc (3 × 75 mL). The combined organic layers were washed with saturated aqueous NaCl and dried (Na_2SO_4). Evaporation of the volatiles left a crude acid which was esterified by using CH_2N_2 in Et_2O–MeOH (4:1). Purification via flash LC with 25% EtOAC–hexane gave 2.4 g (53%) of ester **28** as a viscous oil: R_f (0.57, 30% EtOAc–hexane); ^1H NMR (490 MHz, $CDCl_3$) δ 1.27 (s, 3 H), 1.4 (s, 3 H), (m, 1 H), (m, 1 H), 2.12 (m, 1 H), 3.32 (s, 3 H), 3.73 (s, 3 H), 3.76 (s, 3 H), 4.06 (dd, 1 H, *J* = 6.3, 1.5 Hz), 4.16 (dd, 1 H, *J* = 8, 2.5 Hz), 4.22 (d, 1 H, *J* = 11.1 Hz), 4.35 (d, 1 H, *J* = 11.5 Hz), 4.49 (d, 1 H, *J* = 6.1 Hz), 4.54 (d, 1 H, *J* = 11.4 Hz), 4.61 (d, 1 H, *J* = 11.1 Hz), 4.69 (dd, 1 H, *J* = 4.6, 1.5 Hz), 4.93 (s, 1 H), 6.84 (d, 2 H, *J* = 8.7 Hz), 7.30 (m, 7 H); IR ($CHCl_3$) 1747 cm^{-1}; MS, *m/e* no M^+, 501, (M^+ - 15) 393, 333, 211, 184, 121 (100); chemical ionization (isobutane carrier gas) 517 (M^+ + 1).

Methyl (Methyl 6-deoxy-2,3-*O*-(1-methylethylidene)-5-*O*-(phenylmethyl)-L-*glycero*-β-D-*allo*-octofuranosid)uronate (29). Ester **28** (2.48 g, 4.9 mmol) was dissolved in CH_2Cl_2 (20 mL) followed by the addition of H_2O (1 mL) and DDQ (1.12 g, 4.9 mmol). The color gradually changed from a deep green to yellow-orange as the reaction proceeded. After 24 h, the reaction was diluted with CH_2Cl_2 (50 mL) and poured



35

36 R = Me; R' = Bn

37 R = Me; R' = H

1 R = R' = H = octosyl acid A

Figure 6.

into saturated aqueous $NaHCO_3$. The organic phase was repeatedly washed with $NaHCO_3$ (saturated) until the aqueous layer was colorless and dried over $MgSO_4$. The residue, upon evaporation of the volatiles, was purified (flash LC, 30% EtOH–hexane) to give 1.16 g (62%) of **29** as a colorless oil which solidified on standing: mp 57–58 °C (Et_2O–hexane); R_f 0.23; ^1H NMR δ 1.28 (s, 3 H), 1.47 (s, 3 H), 2.01 (m, 2 H), 3.01 (d, 1 H, J = 5.1 Hz), 3.36 (s, 3 H), 3.76 (s, 3 H), 3.85 (dt, 1 H, J = 8.4, 3.3 Hz), 4.11 (dd, 1 H, J = 7.0, 1.4 Hz), 4.42 (m, 1 H), 4.49 (d, 1 H, J = 6.1 Hz), 4.68 (m, 3 H), 4.94 (s, 1 H), 7.37 (m, 5 H); IR ($CHCl_3$) 3540, 1740 cm^{-1}; MS, m/e no M^+, 381 (M^+ – 15), 349 (100), 223, 173, 131; chemical ionization (isobutane carrier gas) 397 (M^+ + 1). Anal. Calcd for $C_{20}H_{28}O_8$ (396.178): C, 60.57; H, 7.12. Found: C, 60.49, H, 7.20.

Methyl (Methyl 6-deoxy-2,3-*O*-(1-methylethylidene)-5-*O*-(phenylmethyl)-L-*glycero*-β-D-*allo*-octofuranosid)uronate 7-Methanesulfonate (30). Alcohol **29** (616 mg, 1.56 mmol) was dissolved in CH_2Cl_2 (6 mL) and cooled to −20 °C (CCl_4, dry ice). To this solution was added triethylamine (335 μL, 2.4 mmol) followed by methanesulfonyl chloride (228 μL, 2.4 mmol). The mixture was allowed to stir at this temperature for 3 h and at 0 °C for 3 h. The heterogeneous system was diluted with CH_2Cl_2 (50 mL), washed with saturated aqueous $NaHCO_3$, and dried (Na_2SO_4). Flash LC (30% ethyl acetate–hexane) of the residue provided 592 mg (83%) of a colorless oil: $[\alpha]^{23}_D$ −15.6° (*c* 3.1, $CHCl_3$); ^1H NMR (90 MHz, $CDCl_3$) δ 1.28 (s, 3 H), 1.42 (s, 3 H), 2.20 (m, 2 H), 3.10 (s, 3 H), 3.30 (s, 3 H), 3.72 (s, 3 H), 4.06 (s, 1 H, J = 8 Hz), 4.60 (m, 4 H), 4.90 (s, 1 H), 5.25 (dd, 1 H, J = 6, 4 Hz), 7.30 (m, 5 H); IR ($CHCl_3$) 1760, 1355, 1240, 1175 cm^{-1}; MS, m/e no M^+, 459 (M^+ – 15), 428, 427 (100).

Formation of Methyl 6-Deoxy-5-*O*-(phenylmethyl)-L-*glycero*-β-D-*allo*-octofuranuronate 1,2,3-Triacetate 7-Methanesulfonate (31) and Methyl 6-Deoxy-5-*O*-(phenylmethyl)L-*glycero*-α-D-*allo*-octofuranuronate 1,2,3-Triacetate 7-Methanesulfonate (32). The α-mesyloxy ester **30** (292 mg, 0.6160 mg, 0.6160 mmol) was dissolved in MeOH (2.5 mL) and 1 N HCl added (0.5 mL). The reaction mixture was refluxed for 1.5 h, cooled to room temperature, and neutralized with pyridine. The crude reaction mixture was concentrated and the residue dissolved in pyridine (3 mL) and treated with acetic anhydride (0.75 mL) for 5 h. The mixture was diluted with EtOAc and poured into aqueous $CuSO_4$. The layers were separated, and the aqueous phase was extracted with EtOAc (2 × 30 mL). The organic layers were combined, washed with H_2O followed by saturated aqueous $NaHCO_3$, and dried (Na_2SO_4). The solution was concentrated and the residue purified via flash LC with 50% ethyl acetate–hexane to give 248 mg of a 3:1 mixture of anomeric methyl glycosides. This mixture was suitable for subsequent reactions, without separation of the individual anomers.

The methyl glycoside mixture from the above experiment (240 mg, 0.4773 mmol) was dissolved in CH_2Cl_2 (2 mL) and cooled to 0 °C. To this solution were added acetic anhydride (0.45 mL, 4.74 mmol), acetic acid (0.14 mL, 2.37 mmol), and concentrated H_2SO_4 (25 μL, 0.4773 mmol). The reaction was stirred at 0 °C for 1 h, diluted with EtOAc (50 mL), washed with saturated aqueous $NaHCO_3$, H_2O, and brine, and dried ($MgSO_4$). Flash LC with 50% EtOAc-hexane gave 190 mg (76%) combined yield of the two anomeric acetates. α-Anomer: 38 mg; ^1H NMR (250 MHz, $CDCl_3$) δ 2.05 (s, 3 H), 2.11 (s, 6 H), 3.18 (s, 3 H), 3.78 (s, 3 H), 3.96 (dt, 1 H, J = 10.3, 2.6 Hz), 4.28 (t, 1 H, J = 2.5 Hz), 4.71 (s, 2 H), 5.5 (dd, 1 H, J = 4.7, 3.3 Hz), 5.28 (dd, 1 H, J = 10.7, 2.7 Hz), 5.40 (dd, 1 H, J = 6.7, 2.5 Hz), 6.37 (d, 1 H, J = 4.6 Hz), 7.36 (m, 5 H). β-Anomer (major): 152 mg; ^1H NMR (250 MHz, $CDCl_3$) δ 1.95 (s, 3 H), 2.02 (s, 3 H), 2.12 (s, 3 H), 3.16 (s, 3 H), 3.77 (s, 3 H), 3.92 (dt, 1 H, J = 6.8, 3.4 Hz), 4.27 (dd, 1 H, J = 7.1, 3.9 Hz), 4.72 (dd, 2 H, J_{ab} = 10.9 Hz), 5.27 (dd, 1 H, J = 10.1, 3.4 Hz), 5.37 (d, 1 H, J = 4.8 Hz), 5.50 (dd, 1 H, J = 7.0, 4.9 Hz), 6.15 (s, 1 H), 7.34 (m, 5 H).

Formation of Methyl 1,6-Dideoxy-1-[3,4-dihydro-5-(methoxycarbonyl)-2,4-dioxo-1(2*H*)-pyrimidinyl]-5-*O*-(phenylmethyl)-L-*glycero*-β-*allo*-octofuranuronate 2,3-Diacetate 7-Methanesulfonate (33). The triacetate mixture **31** and **32** (175 mg, 0.3277 mmol) was dissolved in dry CH_3CN (1 mL) and cooled to 0 °C. Freshly distilled 2,4-(disilyloxy)-5-carbomethoxypyrimidine (200 mg, 0.640 mmol) was added via syringe followed by trimethylsilyl triflate (126 μL, 0.65 mmol). The reaction was stirred at 0 °C for 3 h and at room temperature for 5 h, at which point it was diluted with $CHCl_3$ (75 mL) and poured into saturated aqueous $NaHCO_3$. The organic phase was washed with saturated aqueous NaCl and dried with Na_2SO_4. Flash LC (40% EtOAc–CH_2Cl_2) of the residue after evaporation of the volatiles gave 192 mg (91%) of **33** as a white solid: mp 154–156 °C; $[\alpha]^{23}_D$ +1.2° (*c* 7.15, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$) δ 2.03 (s, 3 H), 2.13 (s, 3 H), 3.17 (s, 3 H), 3.75 (s, 3 H), 3.77 (s, 3 H), 4.00 (m, 1 H), 4.24 (m, 1 H), 4.77 (dd, 2 H, J = 9.3 Hz), 5.19 (dd, 1 H, J = 10.1, 3.4 Hz), 5.45 (t, 1 H, J = 6 Hz), 5.53 (dd, 1 H, J = 10, 4.6 Hz), 5.93 (d, 1 H, J = 5.8 Hz), 7.35 (m, 5 H), 8.30 (br s, 1 H), 8.37 (s, 1 H); IR ($CHCl_3$) 3500, 3380, 1755, 1725 cm^{-1}; MS, m/e chemical ionization (isobutane carrier gas) 657 (M^+ + 1). Anal. Calcd for $C_{27}H_{32}N_2O_{15}S$ (656.152): C, 49.37; H, 4.91; N, 4.26. Found: C, 49.20; H, 4.86; N, 3.86.

Formation of Methyl 1,6-Dideoxy-1-[3,4-dihydro-5-(methoxycarbonyl)-2,4-dioxo-1(2*H*)-pyrimidinyl]-5-*O*-(phenylmethyl)-L-*glycero*-β-*allo*-octofuranuronate 7-Methanesulfonate (34). Nucleoside **33** (83 mg, 0.1266 mmol) was dissolved in MeOH (0.5 mL) and treated with NaOMe (14 mg, 0.2532 mmol). The reaction mixture was stirred for 1.5 h, at which point TLC indicated total consumption of starting material. The mixture was neutralized with Dowex 50W-X8 (H^+ form), filtered, and concentrated. The residue was passed through a short column of silica gel with 5% MeOH–$CHCl_3$ to elute the product. Compound **34** (60 mg, 84% yield) was obtained as an amorphous powder and directly used in the next experiment.

Formation of Methyl 3,7-Anhydro-1,6-dideoxy-1-[5-(methoxycarbonyl)-3,4-dihydro-2,4-dioxo-1(2*H*)-pyrimidinyl]-5-*O*-(phenylmethyl)-D-*glycero*-β-D-*allo*-octofuranuronate (36). Diol **34** (37.0 mg, 0.0653 mmol) was dissolved in MeOH (1 mL). To this solution was added n-Bu_2SnO (18 mg, 0.0718 mmol) and the reaction mixture refluxed until homogeneous (1 h). The methanol was removed in vacuo and DMF (1 mL) added. The mixture was stirred until homogeneous (ca. 5 min), at which point CsF (10 mg, 0.0658 mmol) was added and the contents were heated at 60 °C for 8 h and finally stirred at room temperature for 9 h. The DMF was removed in vacuo and the residue taken up in $CHCl_3$ (5 mL) and aqueous saturated NaCl (1 mL) and stirred rapidly for 15 min. The mixture was poured into $CHCl_3$ (50 mL) and separated and the organic layer dried ($MgSO_4$). Flash LC (7% MeOH–$CHCl_3$) gave 24 mg (77%) of compound **36**: $[\alpha]^{23}_D$ +29.8° (*c* 0.225, $CHCl_3$); ^1H NMR (250 MHz, $CDCl_3$) δ 2.27 (m, 1 H), 3.68 (s, 3 H), 3.73 (s, 3 H), 4.13 (m, 2 H), 4.37 (br s, 1 H), 4.50 (d, 1 H, J = 4 Hz), 4.55 (dd, 1 H, J = 12, 4 Hz), 4.87 (dd, 2 H, J_{AB} = 13 Hz), 5.86 (s, 1 H), 7.40 (m, 5 H), 8.97 (s, 1 H); IR ($CHCl_3$) 1750, 1720, 1695 cm^{-1}; MS, m/e desorption chemical ionization (isobutane carrier gas) 477 (M^+ + 1). Anal. Calcd for $C_{22}H_{24}N_2O_{11}$: C, 55.44; H, 5.07; N, 5.87. Found: C, 55.21; H, 5.20; N, 5.64.

Formation of Methyl 3,7-Anhydro-1,6-dideoxy-1-[3,4-dihydro-5-(methoxycarbonyl)-2,4-dioxo-1(2*H*)-pyrimidinyl]-D-*glycero*-β-D-*allo*-octofuranuronate (37). Pyran **35** (37 mg, 0.0777 mmol) in THF (0.5 mL) was transferred (canulla) to a THF (0.5 mL) solution containing $Pd(OH)_2$ (120 mg) that had been presaturated with H_2 (balloon, 30 min). Further washings of the substrate flask with THF (2 × 0.25 mL) brought the concentration to ca. 0.04 M. H_2 was bubbled through the system for an additional 15 min, at which time the solution was filtered and concentrated. The residue that remained was purified (flash LC, 10% MeOH–$CHCl_3$) providing 24 mg (80%) of **37** as a white solid: mp 184–186 °C; $[\alpha]^{23}_D$ +6.4° (*c* 0.265, $CHCl_3$); ^1H NMR (10% CD_3OD–$CDCl_3$) δ 1.78 (ddd, 1 H, J = 13.4, 9.4 Hz, 2.2 Hz), 2.17 (dt, 1 H, J = 14.5, 3.2 Hz), 3.73 (s, 3 H), 3.81 (s, 3 H), 3.89 (dd, 1 H, J = 10.1, 4.1 Hz), 4.06 (dd, 1 H, J = 10.2, 2.3 Hz), 4.24 (d, 1 H, J = 4.0 Hz) 4.56 (dd, 1 H, J = 11.2, 3.2 Hz), 4.59 (m, 1 H), 5.71 (s, 1 H), 8.89 (s, 1 H); IR (KBr pellet, 1%) 3400, 1745, 1725, 1620 cm^{-1}; MS, m/e no M^+, 311, 312, 223, 221, 175, 157, 142 (100). These spectra were identical with those of the authentic sample of **37** prepared from natural octosyl acid.

Synthetic Octosyl Acid (1). Pyran **37** (11 mg, 0.0285 mmol) was dissolved in H_2O–THF (300 μL, 2:1) and $LiOH{\cdot}H_2O$ (2.5 mg, 0.06 mmol) added, and the reaction was stirred for 2 h at room temperature. THF was evaporated off with the aid of a stream of N_2 and the remaining aqueous solution acidified (Dowex IR-40, H^+ form). The reaction mixture was filtered and concentrated to give 8 mg (78%) of a white solid: mp 260–263 °C dec; $[\alpha]^{23}_D$ +9.1° (*c* 0.8, 1 N NaOH); the ^1H NMR (250 MHz, DMSO-d_6) was similar to a partially decomposed authentic sample obtained from Professor Isono.

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Registry No. 1, 55728-21-7; **4a**, 54125-02-9; **5**, 33985-40-9; **7**, 99441-05-1; **8**, 101696-46-2; **9**, 101696-47-3; **10**, 116261-35-9; **11**, 116185-25-2; **12**, 116185-26-3; **13**, 116185-27-4; **14**, 116185-28-5; α-**16**, 116185-29-6; β-**16**, 116185-30-9; α-**17**, 116185-31-0; β-**17**, 116185-32-1;

18, 65906-88-9; 19, 116210-23-2; 19 (de-N-benzyl derivative), 116185-33-2; 20, 116185-34-3; 21, 116185-35-4; 22, 116185-36-5; 23, 116185-37-6; 24, 116185-38-7; 27, 101696-49-5; 28, 101696-52-0; 29, 101696-64-4; 30, 101696-53-1; 31, 101696-59-7; 32, 101696-58-6; 33, 101696-60-0; 34, 101696-61-1; 36, 116185-23-0; 37, 116185-24-1.

Supplementary Material Available: Experimental procedures and spectral characterization for compounds in the 7′-8′ oxido route, ORTEP drawings and tables containing fractional coordinates, temperature factors, bond distances, bond angles, torsional angles, and anisotropic temperature factors for compounds **5** and **7** (18 pages). Ordering information is given on any current masthead page.

Kinetics of the Anion-Catalyzed Michael Reaction of Silyl Ketene Acetals. Initiation and Propagation Steps of Group Transfer Polymerization†

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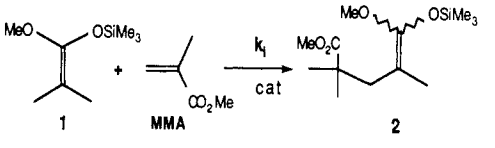
Abstract: The kinetics of the first three steps of "group transfer polymerization" (GTP) have been studied by stopped-flow FT-IR spectroscopy. The kinetic orders of the reaction of dimethylketene methyl trimethylsilyl acetal (**1**) with methyl methacrylate (MMA) have been determined for three anionic catalysts. The reactions catalyzed by bifluoride and benzoate salts were second and first order in catalyst, respectively, while a nonintegral rate was observed for a bibenzoate salt. The first-order rate dependence on fluoride donor **5** suggests that the second-order rate dependence on bifluoride results from the reaction of two HF_2^- ions and the initiator (**1**) to yield $H_2F_3^-$ and a 1:1 complex of fluoride ion and **1**. The activity of catalyst is primarily determined by the structure of the anion. The anions studied can be ranked in order of decreasing reactivity: $HF_2^- > C_6H_5CO_2^- > [(C_6H_5CO_2)_2H]^-$. The individual rates for the initiation (k_i) and the first (k_p^1) and second (k_p^2) propagation steps catalyzed by bibenzoate were determined with the following result: $k_i \approx k_p^1 \approx k_p^2$. It was found also that $k_i \approx k_p^1$ when the catalyst was benzoate. This study has demonstrated that $k_i \geq k_p$ for GTP, which is a kinetic requirement for producing polymer with low polydispersity.

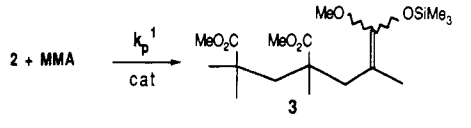
Previous communications from these laboratories have reported controlled polymerization of methacrylate monomers at ambient temperatures initiated by silyl ketene acetals in the presence of a suitable catalyst (group transfer polymerization, GTP).[1,2] The polymerization proceeds by repeated Michael additions of monomer to a growing chain end carrying the silyl ketene acetal functionality. The emphasis of most published work on GTP has been on utility and synthetic aspects of the process. Sogah and Farnham[3] provided compelling evidence for *intramolecular* silicon transfer based on exchange experiments. On the basis of ab initio calculations,[4] carbon–carbon bond formation appears to be the first event after formation of a pentavalent complex between the catalyst and the silyl ketene acetal. Wnek also reached a similar conclusion in a more recent study.[5] Bandermann has reported some kinetic results for GTP in acetonitrile solution,[6] but his work was complicated by side reactions. Müller and Mai[7,8] have also published the results of their kinetic investigations of GTP. The emphasis of Müller's work was on average propagation rates where the starting ratio of MMA to initiator was usually in excess of 100 and primarily involved catalysis by tris(dimethylamino)-sulfonium bifluoride, $TASHF_2$.

Reported here is a kinetic investigation of the anion-catalyzed reaction of dimethylketene methyl trimethylsilyl acetal (**1**) with methyl methacrylate (MMA). The rates for the initiation step and first two propagation steps of GTP have been measured individually using stopped-flow Fourier transform infrared spectroscopy (see Schemes I–III).[9] The discrete study of each of these three steps relied on independent synthesis of intermediates **2** and **3**.

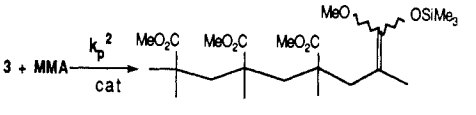
Scheme I



Scheme II



Scheme III



Experimental Section

Materials. Tetrahydrofuran (THF) and pentane were distilled from sodium and benzophenone. Acetonitrile (CH_3CN) was distilled from CaH_2. Solvents were stored and handled in a drybox. Commercially available methyl methacrylate was passed through a short column of

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(1) (a) Webster, O. W.; Hertler, W. R.; Sogah, D. Y.; Farnham, W. B.; Rajan-Babu, T. V. *J. Macromol. Sci., Chem.* **1984**, *A21* (8 and 9), 943. (b) Sogah, D. Y.; Hertler, W. R.; Webster, O. W.; Cohen, G. W. *Macromolecules* **1987**, *20*, 1473–1488, and references cited therein.

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(3) Sogah, D. Y.; Farnham, W. B. *Organosilicon and Bioorganosilicon Chemistry: Structures, Bonding, Reactivity and Synthetic Application*; Sakurai, H., Ed.; Wiley: New York, 1985; Chapter 20.

(4) Dixon, D. A.; Sogah, D. Y.; Farnham, W. B., to be submitted for publication. Ab initio molecular orbital calculations using double-ζ basis sets augmented by polarization functions have been performed on model systems on the GTP potential energy surface. The results show a preference for a pentavalent anionic silicon intermediate and a hexavalent transition state for transfer of the silicon.

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