Table I. Proton Chemical Shifts (ppm) and Coupling Constants (Hz) for Gangliotriaosylceramide (1)[a]

residue	H-1 ($J_{1,2}$)	H-2 ($J_{2,3}$)	H-3 ($J_{3,4}$)	H-4 ($J_{4,5}$)	H-5 ($J_{5,6}$)	H-6 ($J_{6,6}$)	H-8
I	4.161[b] (7.8)	3.036 (8.2)	3.40[e] (8.8)	3.288[c] (10.3)	3.335[f](5.8, <1.5)	3.745, 3.598 (−10.8)	
II	4.222[c] (7.8)	3.245 (8.9)	3.519 (2.0)	3.789[d] (<1.5)	3.500 (5.0, 5.0)	3.604, 3.478 (−11.5)	
III	4.462[d] (8.4)	3.614 (10.0)	3.519 (2.5)	3.614 (<1.5)	3.293[f](6.3, 3.8)	3.478, 3.40[e] (−10.5)	1.884
R	3.442,[b] 3.987 (3.0, 3.9, $J_{1,1}$ 9.3)	3.768 (7.8)	3.870 (7.4)	5.346 (15.2)	5.535 (7.3, 7.3)	1.932	2.021 ($J_{8,9}$ = 7.3)

[a] Obtained at 500 MHz and 30 °C in Me_2SO-d_6-D_2O (98:2, v/v), estimated error ±0.001 ppm and ±0.5 Hz. [b,c,d] Long-range, interresidue coupling demonstrated in 2-D-NOE spectrum. [e] Overlapped with HOD peak. [f] Assignments may be interchanged.

magnetization. Acquisition after a mixing delay, a third 90° pulse, and an additional delay of $^1/_2t_1$ is used to establish a second time domain, t_2. Mixing and pulse times were 0.5 s and 10 μs, respectively. Zero filling and a window function of $\cos^2$ (phase shifted by $\pi/4$) were used in both dimensions. Phase cycling and a small random increment added to the mixing delay were used to suppress J peaks. Processing and graphical identification of connected resonances is similar to that in the 2-D-SECSY experiment. 2-D-NOE data for **1** are included in Figure 1b and discussed below.

Spectral analysis begins by locating the oligosaccharide anomeric (H-1) protons in the 1-D spectrum, easily identified by their downfield chemical shifts (4.0–5.0 ppm) and single couplings. The anomeric region of **1** (Figure 1a) contains three doublets, indicating three aldose or aldoside residues are present, arbitrarily labeled I–III with increasing H-1 deshielding. The chemical shifts and large (>5 Hz) couplings of these protons indicate that each residue is β-pyranosidically linked. The equal intensity of these three doublets and the lack of an α-anomeric resonance confirm that none of the anomeric centers is free and mutarotating. Thus, **1** must be a trisaccharide β-glycosidically linked to an aglycone. The intense alkyl methyl and methylene resonances at 0.852 and 1.233 ppm, respectively, and the distinct subspectrum of the 2-acylamido-1,3-dihydroxy-4-alkenyl fragment[7] (R, Table I) indicate the aglycone is 1-O-linked ceramide.

Beginning with the anomeric resonances, three series of J connectivities are apparent in the 2D-SECSY spectrum (Figure 1b). With these connectivities and integration data as guides, all resonances of each residue of **1** are revealed and assigned (Table I). Each residue manifests a seven-spin AHMRV(XZ) system,[8] diagnostic of aldohexopyranoside rings. Due to the rigidity of such rings, imparted by chair conformations, and their known Karplus relationship,[9] the coupling constants observed between the five ring protons of each residue (Table I) dictate its stereochemistry. Thus, residue I has a *gluco* configuration, and II and III have a *galacto* configuration. The characteristic[2] downfield chemical shifts of H-1 and H-2 of residue III, but not I and II, indicate III is an *N*-acylhexosamine and I and II are hexoses. The three-proton singlet at 1.884 ppm indicates III is *N*-acetylated. Thus, I–III are, respectively, β-glucopyranosyl, β-galactopyranosyl, and 2-acetamido-2-deoxy-β-galactopyranosyl residues.[10] A J connectivity series is also seen for the ceramide (R) moiety (Figure 1b), confirming the aglycone assignment.

The oligosaccharide sequence and sites of glycosidic linkage are revealed through the 2-D-NOE spectrum. Inspection of the anomeric region reveals three through-space couplings for each anomeric proton, two of which are intraresidue 1,3 and 1,5 axial–axial couplings, used to confirm assignments. The third interresidue coupling observed for each anomeric proton is across the glycosidic linkage and, as noted in Figure 1b, between the following proton pairs: I-1 → R-1a, II-1 → I-4, and III-1 → II-4. Thus, the sequence of **1** must be III (1 → 4) II (1 → 4) I (1 → 1) R and its complete structure is 2-acetamido-2-deoxygalactopyranosyl (β-1 → 4) galactopyranosyl (β-1 → 4) glucopyranosyl (β-1 → 1) ceramide (Figure 1). This structure is in agreement with that assigned through chemical and enzymatic methods.[11]

It should be noted that the total time invested in these 2-D spectra is 23 h. While time consuming on a spectroscopy scale, this is very short compared to the many weeks required for conventional chemical analysis.[12] Finally, we wish to report that since the above study of **1**, we have obtained 2-D-SECSY and 2-D-NOE spectra of four other oligosaccharides, including tetrasaccharides and pentasaccharides with branching structures and α-glycosidic linkages. In all cases a unique and correct primary structure was deduced. Complete analysis of the primary structure of an acetylated disaccharide using similar 2-D proton NMR methods has also been carried out recently in the laboratory of L. D. Hall (personal communication). Thus, the combination of 2-D, and high-field NMR promises to be a powerful new method for the rapid and nondestructive analysis of oligosaccharide primary structure.[13]

Registry No. 1, 82648-57-5.

(7) (a) Yamada, A.; Dabrowski, J.; Hanfland, P.; Egge, H. *Biochim. Biophys. Acta* **1980**, *618*, 473. (b) Dabrowski, J.; Egge, H.; Hanfland, P. *Chem. Phys. Lipids* **1980**, *26*, 187.

(8) By this symbol we mean a first-order seven-spin system in which the first five protons are coupled linearly and the last three protons are coupled circuitally (i.e., ABX pattern). Such a seven-spin pattern is characteristic of an aldohexose when compared with the spin systems expected for other monosaccharide types: AHMR(XZ), aldopentose; AHMRV, aldohexuronic acid, AB-AHM(XZ), ketohexose; A(HJ)MRV(XZ), 2-deoxy-aldohexose; etc.

(9) Altona, C.; Haasnoot, C. A. G. *Org. Magn. Reson.* **1980**, *13*, 417.

(10) All monosaccharide residues are assumed to be of the D configuration.

(11) (a) Kuhn, R.; Wiegandt, H. *Z. Naturforsh.* **1964**, *19b*, 256. (b) Ledeen, R.; Salsman, K. *Biochemistry* **1965**, *4*, 2225.

(12) Ledeen, R. W.; Yu, R. K. *Methods Enzymol.* **1982**, *83*, 139.

(13) This research was supported by USPHS Fellowship 1 F32 HL06442 (T.A.W.K.) and Grant NS 11853, NMSS Grant RG 1289-A-2 (R.K.Y.) and NSF Grant CHE-7916210 (J.H.P.).

Photosensitized [4 + 4] Cycloreversion of Anthracene Dimer via an Electron-Transfer Mechanism[1]

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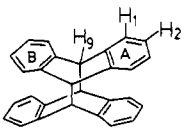
Although much attention has centered on photoinduced electron-transfer reactions in recent years, reports of cycloreversions proceeding by such a mechanism are exiguous and are restricted in [2 + 2] processes.[2] We report here the [4 + 4] cycloreversion of anthracene dimer **1** induced by electron-transfer sensitizers and provide evidence for the detailed mechanism.[3]



1

(1) Publication No. 282 from the Photochemistry Unit, University of Western Ontario.

(2) Cf. inter alia: Majima, T.; Pac, C.; Sakurai, H. *J. Am. Chem. Soc.* **1980**, *102*, 5265. Majima, T.; Pac, C.; Kuba, J.; Sakurai, H. *Tetrahedron Lett.* **1980**, 377. Roth, H.; Lamola, A. A. *J. Am. Chem. Soc.* **1972**, *94*, 1013 (see also ref 5). Okada, K.; Hisamitsu, K.; Mukai, T. *Tetrahedron Lett.* **1981**, 1251. Mukai, T.; Sato, K.; Yamashita, Y. *J. Am. Chem. Soc.* **1981**, *103*, 670.

0002-7863/82/1504-4995$01.25/0

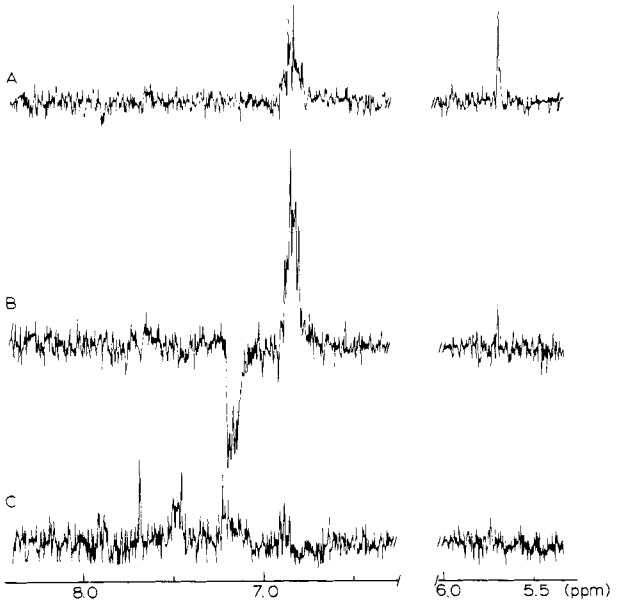
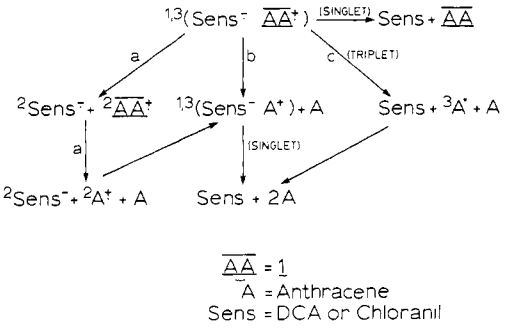


Figure 1. ^{1}H NMR spectrum (100 MHz) of **1** in methylene chloride (2×10^{-3} M) containing 2×10^{-2} M chloranil before (A), during (B), and after (C) irradiation: δ 5.70 (s, H(9) of **1**) 6.90 (m, H(1), H(2) of **1**), 7.20 (m, H(2) of anthracene), 7.48 (m, H(1) of anthracene), 7.69 (s, H(9) of anthracene).

Irradiation of a methylene chloride[4] solution of chloranil (2.03×10^{-2} M) and **1** (2.26×10^{-3} M) at 418 ± 9 nm gave anthracene cleanly (to >70% conversion) with quantum yield 0.58 ± 0.02.[5] Determination of the quantum yield at different concentrations of **1** and extrapolation to infinite concentration gave a limiting quantum yield of 0.75 ± 0.02.[5] Since both singlet and triplet energy transfer is endothermic, an electron-transfer process (ΔG = −32 kcal/mol via the triplet state of chloranil)[6] was surmised, and evidence for this was sought in chemically induced nuclear polarization (CIDNP).[7]

In Figure 1 is shown the observed CIDNP: enhanced absorption in the aromatic region of **1** and emission for the H(2) proton of anthracene. Importantly, excited chloranil and anthracene in the absence of **1** showed no CIDNP effect.[8] Only one of the aromatic protons of **1**, that at lower field, gave an enhanced signal leading to an unsymmetrical signal. That proton should be at H(2) because of the anisotropic effect of the B ring (see **1**).[9] This

Scheme I



polarization requires that the radical–ion intermediate have substantial hyperfine coupling at the H(2) position only, compatible with selective CIDNP on H(2) of the anthracene product. The intact dianthracene cation–radical is expected to possess these properties.[10]

The enhanced absorption of **1** derives from in-solvent-cage back-transfer[11] after intersystem crossing in the initially triplet radical–ion pair. The opposite direction of the anthracene signal can be explained by the occurrence of one or more of the processes a–c in Scheme I. Process a represents bond cleavage from the out-of-cage **1**$^{+\cdot}$. Triplet fragmentation (process b) and triplet back-transfer (process c) in cage are both exothermic, spin-allowed processes (process b, ΔG <−27 kcal/mol; process c, ΔG <−4 kcal/mol).[6] The observation of CIDNP from **1** and chemically formed anthracene clearly demonstrates that the reaction occurs by electron transfer and that the time required for bond cleavage is bounded by two limits: nuclear spin-lattice relaxation times for radicals (10^{-6} s[12]) and the time needed to produce hyperfine interaction of the unpaired electron with the nuclear spin (10^{-9} s[13]).

The reaction could also be sensitized (ΔG = −18 kcal/mol)[6] by dicyanoanthracene (DCA) with a quantum yield 0.11 ± 0.01 at [**1**] = 2.27×10^{-3} M, [DCA] = 5.27×10^{-4} M (λ = 418 ± 9 nm); the limiting quantum yield, at infinite concentration of **1**, was 0.47 ± 0.05.[14] The reaction could be quenched by 1,4-dimethoxybenzene (DMB) and gave a linear (r = 0.999) Stern–Volmer plot for reaction quenching ($k_q\tau$ = 179 ± 7 M^{-1}). A similar Stern–Volmer slope ($k_q\tau$ = 181 ± 2 M^{-1}) for fluorescence quenching by DMB suggests that the latter quenches only the excited singlet state of DCA. The oxidation potential ($E^{ox}_{1/2}$ = 1.55 V vs. SCE)[15] of **1** indicates, however, that **1**$^{+\cdot}$ should be quenched by DMB ($E^{ox}_{1/2}$ = 1.34 V vs. SCE)[16] at a near diffusion

(3) The cycloreversion of **1** by direct irradiation has been recently studied: Yamamoto, S.; Grellman, J.-H.; Weller, A. *Chem. Phys. Lett.* **1980**, *70*, 241. Yamamoto, S.; Grellman, K.-H. *Ibid.* **1982**, *85*, 73. The anion radical of **1**, produced by γ irradiation, has been reported to produce anthracene and its anion radical: Shida, T.; Iwata, S. *J. Chem. Phys.* **1972**, *56*, 2858.

(4) The solubility of **1** was too low in acetonitrile.

(5) Under aerated conditions; under degassed conditions the quantum yield was ca. 10% higher.

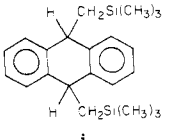
(6) For the free-energy calculation (Knibbe, H.; Rehm, D.; Weller, A. *Ber. Bunsenges Phys. Chem.* **1968**, *72*, 257) values of E^{ox}, E^{red}, and ΔC in acetonitrile were used ($E^{red}_{1/2}$ = 0.02 V vs. SCE (Peover, M. E. *Nature (London)* **1961**, *191*, 702), E_T = 62.3 kcal/mol (Kasha M. *Chem. Rev.* **1947**, *41*, 401) for chloranil; $E^{red}_{1/2}$ = −0.82 V vs. SCE, E_s = 68 kcal/mol (Chandross, E. A.; Ferguson, J. *J. Chem. Phy.* **1967**, *47*, 2557) for DCA). In processes b and c the heat of formation was used: ΔH°_{298} = −15.6 kcal/mol (Bender, P.; Farler, J. *J. Chem.* Soc. **1952**, *74*, 1450) to estimate a minimum value for the free energy gain.

(7) For recent applications of CIDNP to the study of ion–radical processes, see: Roth, H. D.; Schilling, M. L. M. *J. Am. Chem. Soc.* **1980**, *102*, 4303; **1981**, *103*, 7210.

(8) The hyperfine coupling constants for anthracene protons have been reported ($a_{H(1)}$ = −0.306 mT, $a_{H(2)}$ = −0.179 mT, $a_{H(9)}$ = −0.653 mT, g = 2.0028; cf.: Carrington, A.; Dravnicks, F.; Symons, M. C. R. *J. Chem. Soc.* **1959**, 947. Bolton, J. R.; Fraenkel, G. K. *J. Chem. Phys.* **1964**, *40*, 3307). These values indicate that the observed signals from generated anthracene are not attributable to subsequent formation of an anthracene radical cation–chloranil anion radical pair during the course of the reaction. The failure to observe CIDNP from anthracene and excited chloranil may be because of competitive in- and out-of-cage recombination.

(9) For comparable assignments, see: Smith, A. B.; Shoulders, B. A. *J. Phys. Chem.* **1965**, *69*, 2022.

(10) The expected hyperfine coupling at H(1) and H(2) in the radical cation **1**$^{+\cdot}$ is supported by analogy with that of 9,10-bis[(trimethylsilylmethyl)]-9,10-dihydroanthracene (i) radical cation ($a_{H(1)}$ = 0.074 mT, $a_{H(2)}$ = 0.319 mT: Kam. W.; Bock, H. *Chem. Ber.* **1978**, *111*, 3585).



i

(11) a_H and Δg < 0 by analogy with other aromatic hydrocarbons (cf. ref 3). **1** probably has a g value of ~2.0028, whereas chloranil anion radical has a g value of 2.0056.

(12) Kaptein, R. In "Chemically Induced Magnetic Polarization" Muus, L. T., et al., Eds.; Reidel: Dordecht, The Netherlands, 1977; p 14.

(13) Schulten, K.; Staerk, H.; Weller, A.; Werner, H.-J.; Nickel, B. *Z. Phys. Chem.* **1976**, *101*, 371. Werner, H.-J.; Schulten, Z.; Schulten, K. *J. Chem. Phys.* **1977**, *67*, 646. Brocklehurst, B. *J. Chem. Soc., Farad. Trans. 2* **1976**, *72*, 1869; *Chem. Phys. Lett.* **1974**, *28*, 357.

(14) The fluorescence of DCA was quenched by **1** with $k_q\tau$ = 94.2 M^{-1}.

(15) Cyclic voltametry (Pt electrode, scan rate 20 mV/s) of **1** ([**1**] = 8.4×10^{-5} M) in acetonitrile containing 0.1 M tetraethylammonium perchlorate showed that the oxidation process was irreversible. $E^{ox}_{1/2}$ was estimated from $E_p = E_{1/2} - 1.1(RT/nF)$.[16]

(16) Mann, C. K.; Barnes, K. K. "Electrochemical Reaction in Nonaqueous System"; Marcel Dekker: New York, 1970.

rate. This suggests that *if* $1^{+\cdot}$ were involved in the reaction, its lifetime, or that of the ion–pair ($1^{+\cdot}DCA^{-\cdot}$), should be considerably less than the singlet lifetime of DCA (12 ns).[17]

The present evidence restricts the possible pathways to those shown in Scheme I. A thermally forbidden concerted σ-bond cleavage in $1^{+\cdot}$ should require a high activation energy,[18] but the formation of an intermediate short-lived bianthryl diradical (or radical–ion) is a possibility.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, and the National Sciences and Engineering Research Council of Canada for support of this research.

Registry No. 1, 1627-06-1; chloranil, 118-75-2; 9,10-dicyanoanthracene, 1217-45-4; 1,4-dimethoxybenzene, 150-78-7.

(17) τ = 12.2 ns in degassed solution, 11.7 ns under aerated conditions in methylene chloride at room temperature. We thank E. Gudgin and Professor W. R. Ware for this determination.

(18) Dewar, M. J. S.; Kirschner, S. *J. Am. Chem. Soc.* **1975**, *97*, 2931.

Stereocontrolled Total Synthesis of (±)-Maytansinol

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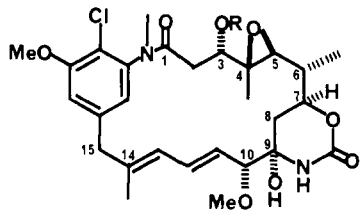
Maytansine (**1**), a novel ansa-macrocyclic lactam from *Maytenus serrata*, *M. buchananii*, etc., has significant in vitro cytotoxicity and in vivo antitumor activity.[1] It was recently synthesized by two groups in racemic and optically active forms.[2] Recent stereochemical advances in the macrocyclic natural product syntheses[3] prompted us to describe our new stereocontrolled total synthesis of racemic maytansinol (**2**). Our goal to this synthesis lies in exploiting the acylic diastereoselective induction of all of the asymmetric carbons, before closing the 19-membered lactam ring starting from one single asymmetric center in a simple molecule.

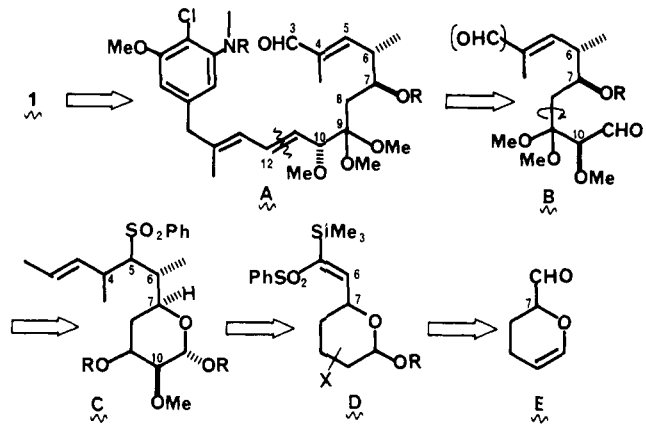


1 R = COCHMeNMeCOMe

2 R = H

The general synthetic strategy toward maytansinoids is illustrated in Scheme I. The common three asymmetric carbons, C-6, -7, and -10 for maytansinoids are included in the intermediate A. Cleavage between C-11 and C-12 of A leads to the pyranosyl ring compound C. The heteroconjugate addition[4] of MeLi accomplishes the complete acyclic stereoselection in the pyranosyl heteroolefin such as D,[5] which is preparable from acrolein dimer

Scheme I



E. The high diastereoselective C–C bond formation was facilitated by efficient conformational and chelational control. The current methodology was also designed for elongation of the C–C chain between C-4 and C-5 effected by the α-sulfonyl carbanion, which was finally removed to form an olefin. The stereochemistry of other asymmetric centers were controlled under new *diastereoselective* methods such as epoxidation,[6] aldol reaction, and so on.

Heteroconjugate addition of MeLi (THF, −78 °C, 5 min) to **3** (Scheme II) was followed by treatments with KF (forming **4**, its carbanion being generated with *n*-BuLi) and 4-bromo-2-pentene to give alkylated products **5** in 92% yield. Selective opening of the oxyrane ring of **5** with sodium *p*-anisyl oxide (5 equiv in refluxing THF) and subsequent trapping with large excess MeI in one pot gave **6** (87%), which was further converted into **8b** (86%) in several steps for a basic cleavage of the glycosidic bond. Thus, **6** was first treated with 2-chloroethanol [containing 10-camphorsulfonic acid (CSA) and $(MeO)_3CH$ at 80° C for 18 h], and the resulting **7** was oxidized with CrO_3–2Py (CH_2Cl_2, room temperature, 0.5 h) and then ketalized with $(MeO)_3CH$ (CSA in MeOH, room temperature 12 h) to give **8a**. It was further converted into the 2-phenylsulfonyl)ethyl glycoside **8b** with sodium thiophenolate (THF, 0 °C to room temperature) and then with MCPBA (dry CH_2Cl_2, 0 °C 0.5 h). Reduction of **8b**[7] with $NaBH_4$ [EtOH–THF (4:1), 80 °C, 1 h, N_2] afforded the open-chain diol **9a** (70%). Each of its two hydroxy groups was selectively protected first with AcCl [1.2 equiv and Py (5 equiv), dry CH_2Cl_2, 0 °C, 20 min] and subsequently with Me_2-*t*-BuSiCl (imidazole in DMF, 70 °C 30 h) to give **9b** (50% overall yield from **7**). Ozonolysis of **9b** (CH_2Cl_2, −78 °C) and workup with Et_3N[8] produced in 99% yield the stereochemically pure unsaturated aldehyde **10** [^1H NMR δ[9] 1.06 (Me, d, J = 7 Hz), 1.78 (Me, s), 3.98 (d, J = 12 Hz), 4.38 (dd, J = 12, 2.5 Hz), 6.48 (d, J = 9 Hz), 9.32 (s); IR ν 1744, 1690 cm^{-1}], which involved the common three asymetric centers for maytansinoids. **10** was converted in three steps to **11** (91%) by successive treatments with (i) pyridinium tosylate [MeOH–$(MeO)_3CH$ (6:1), 0 °C, 2 days], (ii) MeONa [1.5 equiv in MeOH, room temperatures, 45 min], and (iii) CrO_3–2Py (6 equiv in CH_2Cl_2, room temperature, 15 min). The acetal **11** was now ready to be condensed with the aromatic counterpart **15** toward **17**. On the other hand, the phosphorus ylide **15** was prepared in seven steps from the known benzyl iodide **12**[10] via **13** and **14a–d** in 45% overall yield.[11] This ylide was reacted with

(1) (a) Kupchan, S. M.; Komoda, Y.; Branfman, A. R.; Dailey, R. G., Jr.; Zimmerly, V. A.; *J. Am. Chem. Soc.* **1972**, *94*, 1345. (b) Kupchan, S. M.; et al. *J. Org. Chem.* **1977**, *42*, 2349. (c) Extensive clinical and biochemical studies reviewed: Komoda, Y.; Kishi, T. In "Anticancer Agent Based on Natural Product Models"; Cassady, J. M., Douros, J. D., Eds.; (P353-389), Academic Press: New York; Chapter 10.

(2) (a) Meyers, A. I.; Reider, P.; Campbell, A. L. *J. Am. Chem. Soc.* **1980**, *102*, 6579. (b) Corey, E. J.; Weigel, L. O.; Chamberlin, A. R.; Cho, H.; Hua, D. H. *Ibid.* **1980**, *102*, 6615.

(3) For example: "Organic Synthesis Today and Tomorrow"; Trost B. M., Hutchinson, C. R., Eds.; Pergamon Press New York, 1981.

(4) (a) Isobe, M.; Kitamura, M.; Goto, T. *Tetrahedron Lett.* **1979**, 3465; (b) **1980**, *21*, 4727; (c) *Chem. Lett.* 1980, 331.

(5) (a) Isobe, M.; Kitamura, M.; Goto, T. *Tetrahedron Lett.* **1981**, *22*, 239. (b) Isobe, M.; Ichikawa, Y.; Goto, T. *Ibid.* **1981**, *22*, 4287.

(6) Isobe, M.; Kitamura, M.; Mio, S.; Goto, T. *Tetrahedron Lett.* **1982**, *23*, 221.

(7) This particular glycoside, **8b**, was extremely alkaline labile even in the basisity of $NaBH_4$, see also: Narang, S. A.; Bhanot, O. S.; Goodchild, J.; Wightman, R. J.; Dheer, S. K. *J. Am. Chem. Soc.* **1972**, *94*, 6183.

(8) Usage of Et_3N to decompose ozonide was first reported by Isobe et al. (Isobe, M.; Iio, H.; Kawai, T.; Goto T. *Tetrahedron Lett.* **1977**, 703).

(9) ^1H NMR spectra were measured in $CDCl_3$ (δ) at 100 MHz unless specified; IR spectra were taken in CCl_4.

(10) Gotschi, E.; Schneider, F.; Wagner, H.; Bernaner, K. *Org. Prep. Proced. Int.* **1981**, *13*, 23.

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