Cyclization Reactions of Nucleoside Anomeric Radical with Olefin Tethered on Base: Factors That Induce Anomeric Stereochemistry

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Nucleoside anomeric radicals were formed through 1,5-translocation of vinyl radicals generated from the 2,2-dibromovinyl group tethered at the uracil 6-position (**1**, **2**, and **4**) by tin radical. The anomeric radicals attacked the resulting C-6 vinyl group in a 5-*endo-trig* manner to afford anomeric spiro nucleosides (**11**−**13**, **21**, **23**, and **24**) with the 6,1′-etheno bridge as the major cyclized products. The anomeric stereochemistry of the cyclization was found to be affected by the 2′-substituent. To consider the structure of the intermediate anomeric radical, the reaction using α-6-(2,2-dibromovinyl)-2′-deoxyuridine **9** was investigated. The same anomeric *β*/α-stereoselectivity as the counterpart of **2** showed that the nucleoside anomeric radical would have nearly a planar structure and the C1′−N1 bond rotation in the radical is much faster than cyclization. The origin of the minor spiro nucleosides (**14**−**20**, **22**, and **25**−**28**) with the 6,1′-ethano bridge has also been investigated and appeared to be (*E*)-6-(2-bromovinyl)uridine **7E**, a reduced form of **1a**, but not (*Z*)-6-(2-bromovinyl)-uridine **7Z**, which gave a novel type of unstable compound with 6-exomethylene structure **29** through a different reaction pathway. 6-Chloro-8-(2,2-dibromovinyl)purine nucleoside **10** was next studied, and not only 1,5- but also 1,6-translocated products were isolated.

Introduction

Nucleoside anomeric radical formation has been one of the topics regarding DNA and RNA degradation mechanisms by certain anticancer drugs.[1] Anomeric hydrogen was found to be abstracted by aromatic carbon radicals[2] or activated oxygen species,[3] and the resulting anomeric radicals are likely to react with molecular oxygen. This process causes oxidative cleavage of the nucleic acids to the fragments. Regarding synthetic chemistry, however, only three types of methods have been developed to generate the radicals. The first one was manipulation of radical 1,2-acyloxy migration from 2′-deoxy-2′-*β*-bromo-1′-pivaloyloxy-α-uridine, which was successfully applied to the synthesis of C1′ carbon-branched *β*-nucleosides.[4] As the second approach, Goodman and Greenberg have reported *tert*-butylcarbonyl-2′-deoxyuridine, which gives the radical by photolysis.[5] This strategy was applied to study the spectra and structure of the 2′-deoxyuridine-1′-yl radical.[6] The third was utilization of 1,5-translocation of the vinyl radical, which was generated from the 2,2-dibromovinyl group at a base moiety.[7] This reaction gave a variety of types of spiro nucleosides via 5-*endo-trig* cyclization,[8] and we were interested in investigating the precise reaction mechanism for producing them. We wish to report in detail this radical reaction toward 6-(2,2-dibromovinyl)uridine and 9-(*β*-D-ribofuranosyl)-6-chloro-8-(2,2-dibromovinyl)purine derivatives (**1**−**4** and **10**) with some results of (*E*)- and (*Z*)-6-(halovinyl)uridine derivatives **7** and **8**, and also a case of α-2′-deoxyuridine derivative **9** to study the structure of the anomeric radical.

Results and Discussion

Preparation of the Substrates for the Radical Reaction. To introduce the 2,2-dibromovinyl group into the 6-position of uridine, 5′-*O*-(TBDMS)-2′,3′-*O*-isopro-

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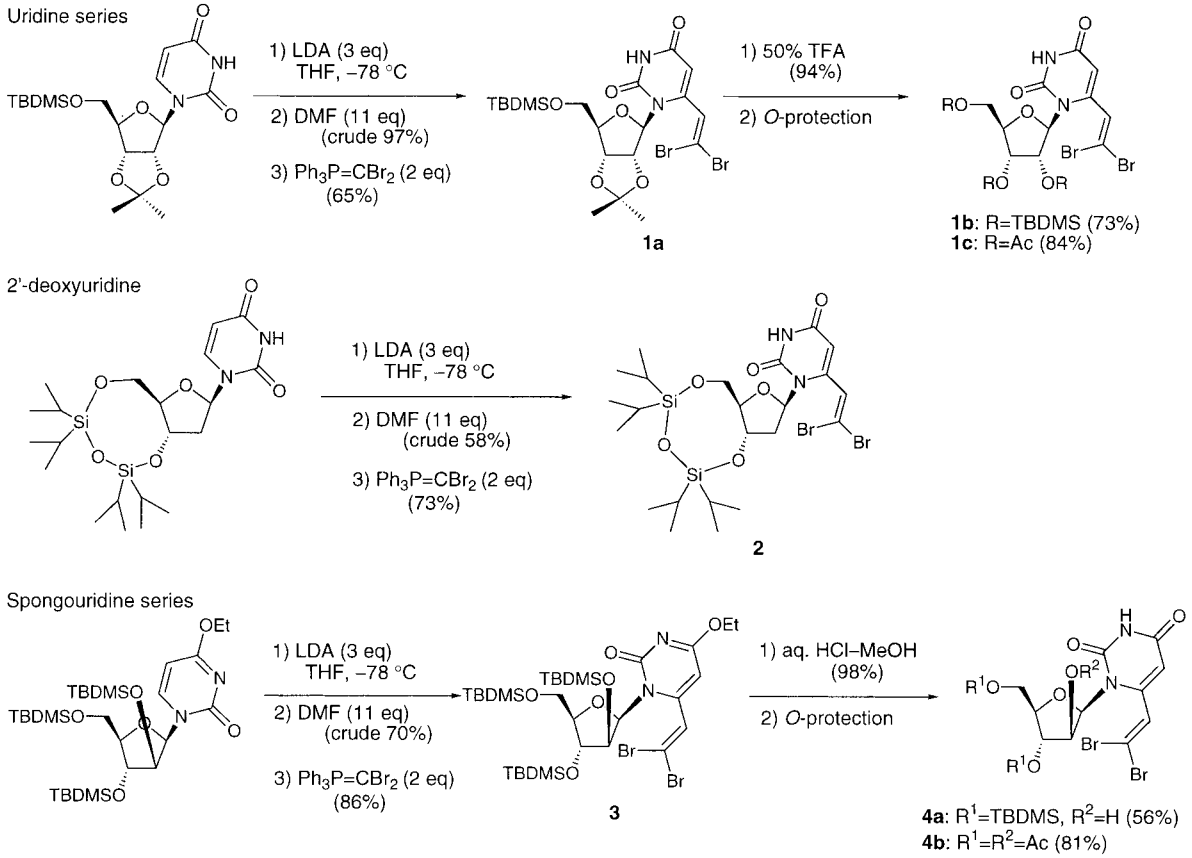
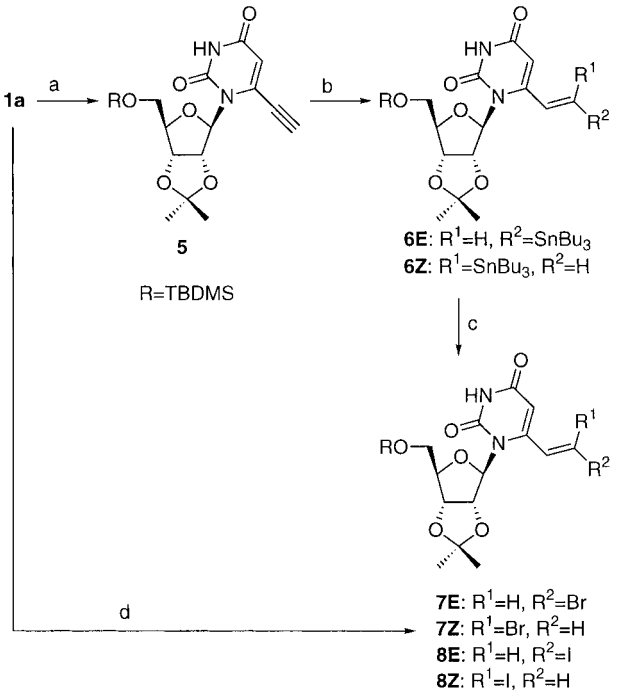
Scheme 1



pylideneuridine was first lithiated with LDA and subsequently treated with DMF for formylation.[9a] The resulting aldehyde, obtained in 97% yield, reacted with dibromomethylene triphenylphosphorane[10] to afford substrate **1a** in 65% yield. Other uridine derivatives protected with 2′,3′,5′-tris-*O*-(TBDMS) and 2′,3′,5′-tri-*O*-acetyl groups, **1b** and **1c**, were prepared from **1a** in 73% and 84% yields, respectively. For a 2′-deoxyuridine derivative, the formylation occurred in 58% yield,[9b] and the following Wittig reaction gave **2** in 73% yield. In the case of an arabinofuranosyl uracil nucleoside, it was necessary to convert the base moiety to 4-ethoxy-2-pyrimidinone for effective lithiation at the 6-position.[9c] The formylation and the following Wittig reaction proceeded in 70% and 86% yields, respectively, to afford **3**. Treatment with aqueous HCl in MeOH and subsequent protection with 3′,5′-bis-*O*-(TBDMS) and 2′,3′,5′-tri-*O*-acetyl groups gave the substrates **4a** and **4b** in 56% and 81% yields, respectively (Scheme 1).

Next, we tried the same synthetic route to obtain (*E*)- and (*Z*)-6-bromovinyluridines **7E** and **7Z** from the 6-formyluridine derivative; however, the Wittig reaction with bromomethylene triphenylphosphorane[11] was unsucssessful.[12] Therefore, both compounds were synthesized from **1a** as follows: BuLi (3 equiv) treatment in THF to afford

Scheme 2[a]



[a] Reagents: (a) BuLi (3 equiv), THF, −78 °C; (b) Bu_3SnH (2 equiv), AIBN (0.5 equiv), C_6H_6, 80 °C; (c) to **7E** or **8**: NBS (2 equiv) or I_2 (1−2 equiv), THF, rt; (d) to **7Z**: 4 mol % $Pd(PPh_3)_4$, Bu_3SnH (2 equiv), C_6H_6, rt.

an acetylene derivative **5** in 83% yield,[10] which was converted to stannylolefins **6E** and **6Z** by regioselective hydrostannylation (49%, *E*:*Z* = 5:1),[13] and the former reacted with NBS to give (*E*)-bromoolefin **7E** (*J* = 17.1

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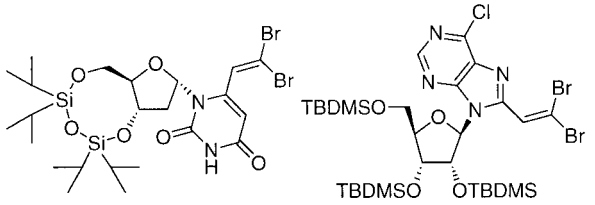
(11) Matsumoto, M.; Kuroda, K. *Tetrahedron Lett.* **1980**, *21*, 4021−4024.

(12) Inseparable mixture was obtained including 6-epoxy and also 6-ethynyl derivatives.

Hz) in 97% yield. On the other hand, Pd-catalyzed reduction of **1a** using Bu_3SnH[14] gave (*Z*)-bromoolefin **7Z** (J = 8.4 Hz) in 40% yield, along with 6-vinyluridine (5%), 6-ethyluridine (**30**, 8%), and the recovery of **1a** (30%). To compare the efficacy of the radical cyclization reaction, both (*E*)- and (*Z*)-6-iodovinyluridines **8E** (J = 14.7 Hz) and **8Z** (J = 9.0 Hz) were also synthesized from (*E*)- and (*Z*)-stannylolefins **6** by reaction with iodine in 99% and 66% yields, respectively (Scheme 2).

α-2′-Deoxyuridine was prepared according to Holý's procedure.[15] The 3′- and 5′-hydroxyls were protected by the 1,1,3,3-tetraisopropyldisiloxane-1,3-diyl (TIPDS) group, and the following formylation with DMF via LDA lithiation and the dibromomethylenation as above afforded dibromoolefin **9** in 28% overall yield. Last, 6-chloropurine nucleoside derivative **10** was synthesized from the 2′,3′,5′-tris-*O*-(TBDMS) protected 6-chloronebularine through the selective C8 lithiation,[16,18c] followed by formylation, and the Wittig reaction sequence in 44% overall yield.



Organostannane-Mediated Radical Reactions and Structure Determination of the Cyclized Products. The radical reaction of each substrate thus obtained above was carried out in a refluxing benzene solution by adding a mixture of 2 equiv of Bu_3SnH and 0.5 equiv of AIBN in benzene over 3 h using a syringe pump (Scheme 3). The cyclized products were isolated by normal-phase HPLC, and the results are summarized in Table 1.

Uridine Series. The spiro structures as well as the anomeric stereochemistry of cyclized products **11**β, **12**β, and **13**β were confirmed by conversion to the reported spiro nucleosides.[17,18] The anisotropic effect of the fixed C2-carbonyl group in the spiro compound toward H2′ is important to determine the base orientation β or α by ^{1}H NMR.[7a] For example, a chemical shift of H2′ in **11**β ($CDCl_3$, TMS) is 5.15 ppm; on the other hand, in **11**α, 4.76 ppm. The structure of **19**β with (8*S*)-configuration was unambiguously determined on the basis of X-ray crystallographic analysis (Figure 1).[19] The ^{1}H NMR chemical shift ($CDCl_3$, TMS) of the 2′-OAc group in **19**β appears at a high field of 1.53 ppm because of shielding effects of the proximal phenyl group.[20] Because the chemical shift of H4′ in the (8*R*)-diastereomer **20**β is also characteristic, it appears in a high field at 3.50 ppm, while **19**β (8*S*) appears at 4.26 ppm. The chemical conversion of benzene adducts of **15**β and **17**β (deprotection followed by acetylation) to **20**β proved the stereochemistry at C8(*R*). The C8 stereochemistry of α-cyclized products **17**α and **19**α was estimated by ^{1}H NMR chemi-

Table 1. Radical-Mediated Cyclization of Nucleosides 1−4 and 7−10

subst	cyclized products (% yield) 6,1′-etheno	β/α	6,1′-ethano	combined yield (%)
1a	**11**β (40), **11**α (3)	13/1	**15**β (3)	46
1b	**12**β (50)		**16**β (4), **17**β (5), **17**α (3)	62
1c	**13**β (40), **13**α (7)	5.7/1	**18**β (2), **19**β (8), **19**α (1), **20**β (5)	63
7E	-		**14**β (31)	31
7Z	-		nd[a]	0
8E	-		**14**β (76)	76
8Z	-		**14**β (77)	77
2	**21**β (23), **21**α (16)	1.4/1	**22**β (7), **22**α (1)	47
9	**21**β (25), **21**α (16)	1.6/1	nd	41
3	nd		nd	0
4a	**23**β (11), **23**α (26)	1/1.4	**25**β (8), **26**β (12)	57
4b	**24**β (12), **24**α (26)	1/2.2	**27**β (8), **27**α (4), **28**β (2), **28**α (7)	59
10	**32**β (18), **32**α (14)	1.3/1	nd	32

[a] Not detected.

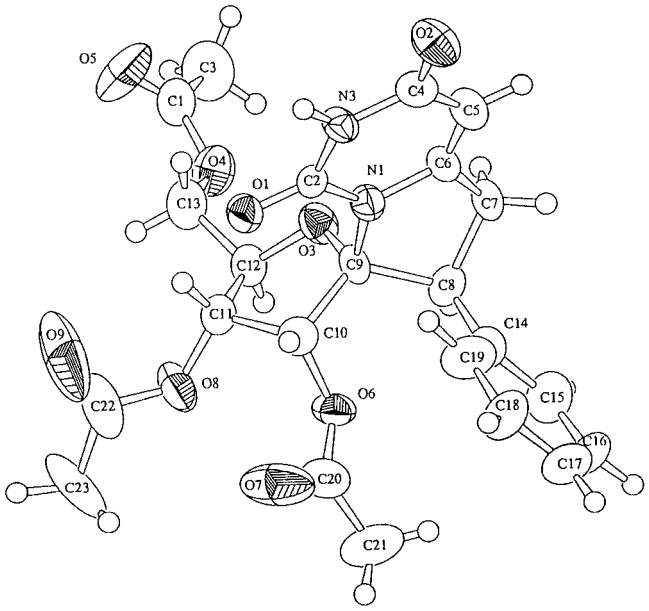


Figure 1. ORTEP drawing of one of the independent molecules of **19**β in the unit cell.

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(18) For syntheses of several types of anomeric spiro nucleosides, see: (a) Kittaka, A.; Tanaka, H.; Kato, H.; Nonaka, Y.; Nakamura, K. T.; Miyasaka, T. *Tetrahedron Lett.* **1997**, *38*, 6421−6424. (b) Kittaka, A.; Tanaka, H.; Kato, H.; Asakura, T.; Nakamura, K. T.; Miyasaka, T. *Nucleic Acids Symp. Ser.* **1997**, *37*, 57−58. (c) Kittaka, A.; Yamada, N.; Tanaka, H.; Nakamura, K. T.; Miyasaka, T. *Nucleosides Nucleotides* **1996**, *15*, 1447−1457. (d) Yoshimura, Y.; Otter, B. A.; Ueda, T.; Matsuda, A. *Chem. Pharm. Bull.* **1992**, *40*, 1761−1769. (e) Sarma, M. S. P.; Megati, S.; Klein, R. S.; Otter, B. A. *Nucleosides Nucleotides* **1995**, *14*, 393−396. (f) Zavgorodny S. G. *Tetrahedron Lett.* **1981**, *22*, 3003−3006. (g) Gimisis, T.; Castellari, C.; Chatgilialoglu, C. *Chem. Commun.* **1997**, 2089−2090. (h) Kittaka, A.; Kato, H.; Tanaka, H.; Nonaka, Y.; Amano, M.; Nakamura, K. T.; Miyasaka, T. *Tetrahedron* **1999**, *55*, 5319−5344.

(19) Experimental details of the X-ray structure determination, ORTEP representations and tables of fractional atomic coordinates, thermal parameters, interatomic distances and angles for **19**β are available in Supporting Information.

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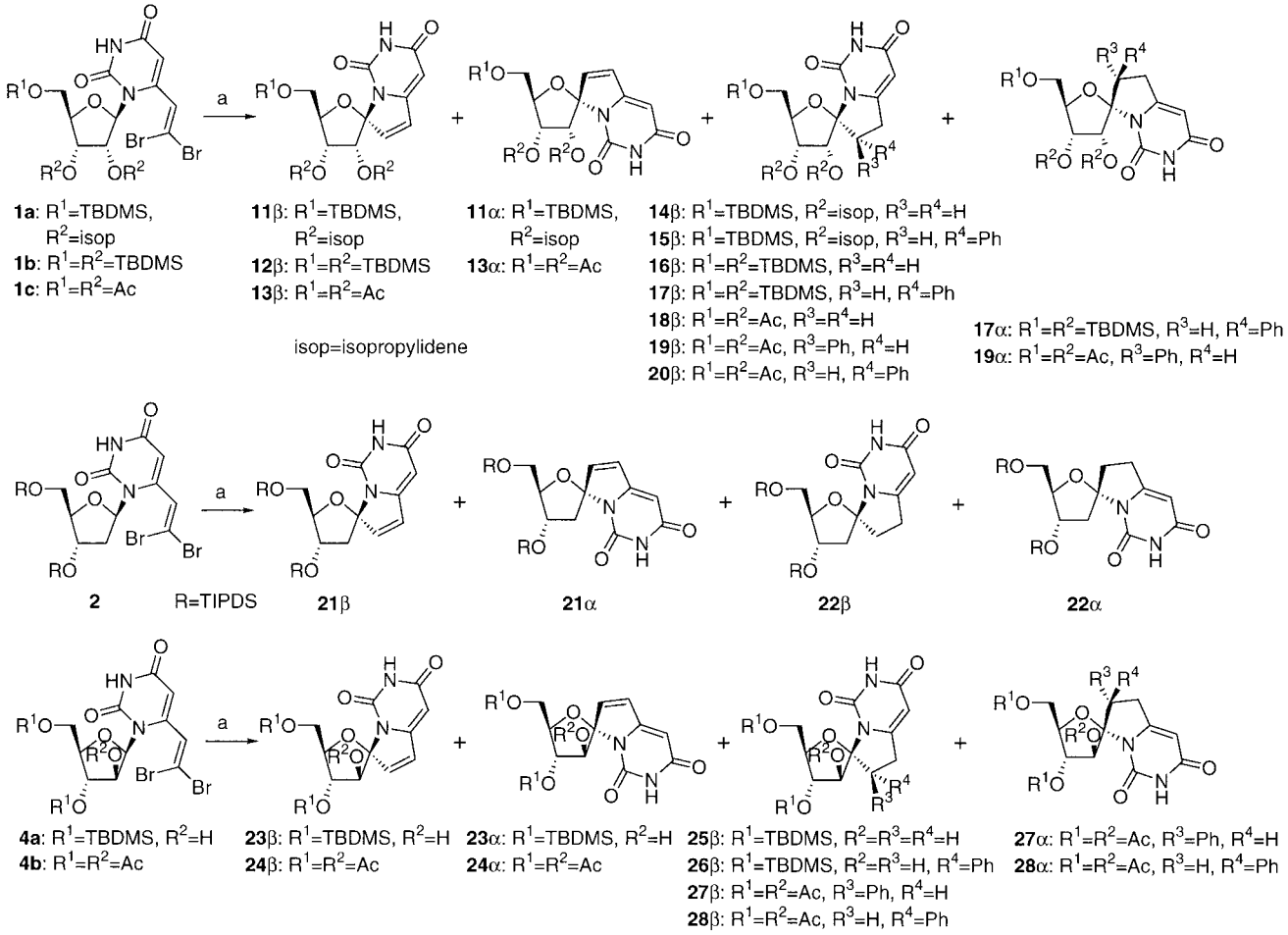
Scheme 3[a]

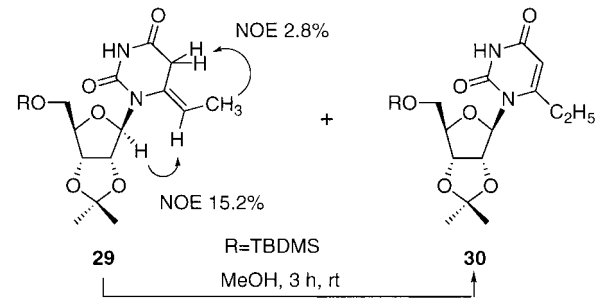


[a] Reagents: (a) Bu_3SnH (2 equiv), AIBN (0.5 equiv), C_6H_6, 80 °C.

cal shifts of H2′ and H3′. These two former **17**α were strongly affected by shielding effects of the phenyl ring (H2′, 3.69 ppm; H3′, 2.86 ppm, then 8*R*), but H2′ of the latter **19**α was not affected (5.28 ppm, presumably 8*S*). In all cases *β*-spiro nucleosides were superior products to the α-spiro nucleosides in this series.

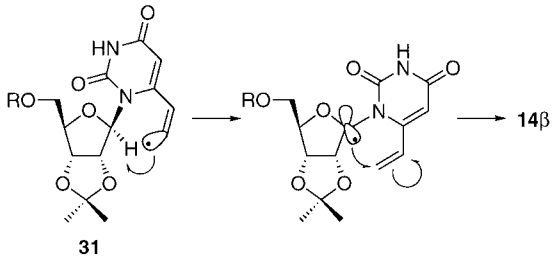
To see the reaction course for the 6,1′-ethano bridge formation, (*E*)- and (*Z*)-bromoolefins (**7E** and **7Z**) were investigated. Although the (*E*)-isomer **7E** gave 6,1′-ethanouridine **14***β* in 31% yield, the (*Z*)-isomer, unexpectedly, afforded no cyclized product. Instead, the products from **7Z** were an unstable exomethylene nucleoside **29** and 6-ethyluridine **30** isolated by HPLC in 33% and 45% yields, respectively (Scheme 4). The former

Scheme 4



compound, showing λ_{max} 235 nm, gradually isomerized to the latter (λ_{max} 259 nm) in a MeOH solution at room temperature during measurement of UV spectra (Supporting Information). Initially obtained 6-ethyluridine **30** was most likely to be converted by this isomerization of **29** during workup. Both (*E*)- and (*Z*)-iodoolefins (**8E** and **8Z**), however, afforded the spiro compound **14***β* in the same yield (77%); therefore, it is clear that once a 6-vinyl radical **31** is formed, 1,5-translocation to the anomeric position followed by 5-*endo-trig* cyclization proceeds with high efficiency (Scheme 5).

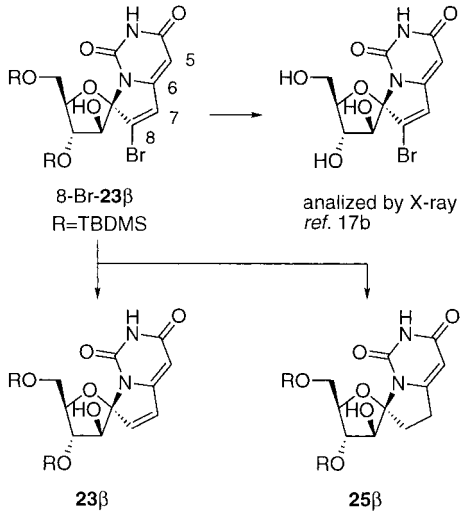
Scheme 5



2′-Deoxyuridines. Cyclized products (**21***β*, **21**α, **22***β*, and **22**α) from 6-(2,2-dibromovinyl)-2′-deoxyuridine **2** were identical with authentic samples after deprotection.[17a] *β*-Selectivity was dropped in the 5-*endo-trig* cyclization step caused by lack of steric hindrance induced by the 2′-α-substituent. Interestingly, this poor *β*/α selectivity was almost the same as that from the α-derivative of **9** (Table 1).

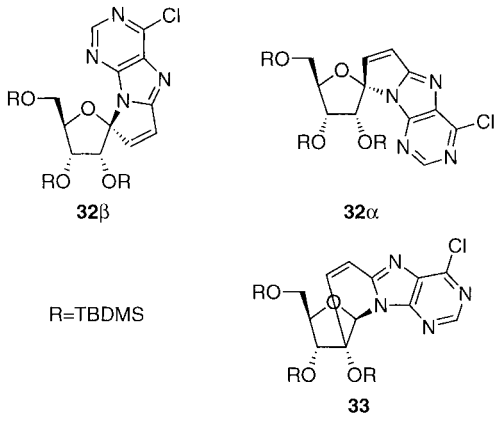
Arabinofuranosyl Uracil Nucleosides. The radical reaction for arabinofuranosyl 6-(2,2-dibromovinyl)-4-ethoxy-2-pyrimidinone nucleoside **3** gave a complex mixture, and no cyclized product was formed. The vinyl radical stabilized by the enone system of the uridine base plays an important role for the 1,5-translocation step.[21] The structures of **23***β* and **25***β* are highly related to the reported compound, i.e., 8-bromo-**23***β*, whose *O*-deprotected structure was proved by X-ray crystallography.[17b] Halogen−lithium exchange reaction of 8-bromo-**23***β* with BuLi (3 equiv) in THF at −70 °C gave **23***β* in 38% yield, and hydrogenation of 8-bromo-**23***β* on 5% Rh−Al in MeOH afforded **25***β* in quantitative yield (Scheme 6).

Scheme 6



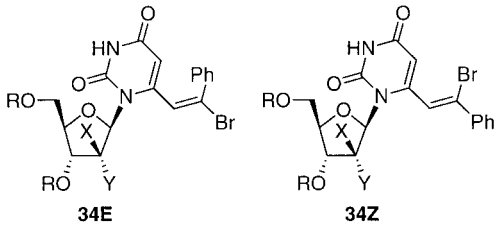
The anisotropic effect of the C2-carbonyl group toward H2′ and H4′ is again considerable to determine the base orientation *β* or α by ^{1}H NMR.[7a] For example, chemical shifts of H2′ and H4′ in $CDCl_3$ are as follows (*δ* ppm): **23***β*, 5.76 and 4.32 ppm; **23**α, 6.37 and 4.88 ppm, respectively. The structures of cyclized products **27** and **28** with the C8-phenyl group were analyzed by combination of chemical shifts of H2′ and 2′-OAc: the anomeric *β* or α configuration was confirmed on the basis of deshielding effects of the C2-carbonyl: **27***β* (H2′, 5.19) and **28***β* (H2′, 5.63) as compared to **27**α (H2′, 6.88) and **28**α (H2′, 6.19). The stereocenter of C8 was determined by shielding effects of the phenyl group, **27***β* (H2′, 5.19, 8*S*) vs **28***β* (H2′, 5.63, 8*R*) and **27**α (2′-OAc, 1.95, 8*S*) vs **28**α (2′-OAc, 1.79, 8*R*). Both cases showed decreased proportions of *β*-isomers.

Ribofuranosylpurine Nucleoside. Since the vinyl group is bound to a five-membered imidazole ring, the distance between the vinyl radical and H1′ is longer than that of uracil cases. Therefore, the efficiency of 1,5-translocation would be comparatively lower and the combined chemical yield of spiro products decreased to 32% (Table 1), and 1,6-translocation[22] product **33** was also obtained. The decreased *β*/α ratio could be explained by taking into consideration the compact imidazole ring system, which does not significantly interfere with the 2′-hydroxyl group. The structure of *β* or α of the 5-*endo*-cyclized products was determined by comparing ^{1}H NMR chemical shifts of the combination of H2′/H4′, affected by the N3-anisotropic effect.[23] Namely, *β*-cyclized **32***β* showed H2′ (5.10 ppm, deshielded)/H4′ (4.25 ppm); on the other hand, α-cyclized **32**α appeared as H2′ (4.46 ppm)/H4′ (4.78 ppm, deshielded).



The Plausible Reaction Mechanism. The first step of this cyclization reaction would be a less-hindered bromine atom abstraction from the 2,2-dibromovinyl group by tin radical to produce (*Z*)-monobromovinyl radical **A**. The equilibrium[24] gives (*E*)-bromovinyl radical **B**, which makes possible 1,5-translocation to generate stable anomeric radical **C**. According to the anomeric stereoselectivity of the subsequent 5-*endo-trig* cyclization step, the direction and bulkiness of the 2′-substituent seemed to play an important role. The structure of **C** appears to be almost planar, and the C1′−N1 bond rotation in **C** would be faster than the cyclization on the basis of our synthetic results using the *β*- and α-2′-deoxyuridine derivatives **2** and **9** (Table 1).[7b,25] From **C**, C1′-carbon forms gradually into an sp^3 structure on the route to the transition states **D***β* and **D**α for cyclization. The energy difference between the two transition states seems to be caused by repulsion between the C2 carbonyl and the 2′-substituent (Scheme 7). After cyclization, alkyl radicals **E** that were stabilized by an enone system appeared and eliminated a *β*-bromine atom.[26]

When vinyl radicals **A** and **B**, which were stabilized by a bromine atom, reacted with an H source or the benzene solvent, the four bromovinyl derivatives **7E**, **7Z**,



34E, and **34Z** could be produced, and **7E** and **34E** would be the origins of 6,1′-ethanobridged spiro nucleosides.[27]

(21) The radical reaction of **3** using Bu_3SnD instead of Bu_3SnH afforded neither a D-incorporated product at the anomeric position nor a cyclized product.

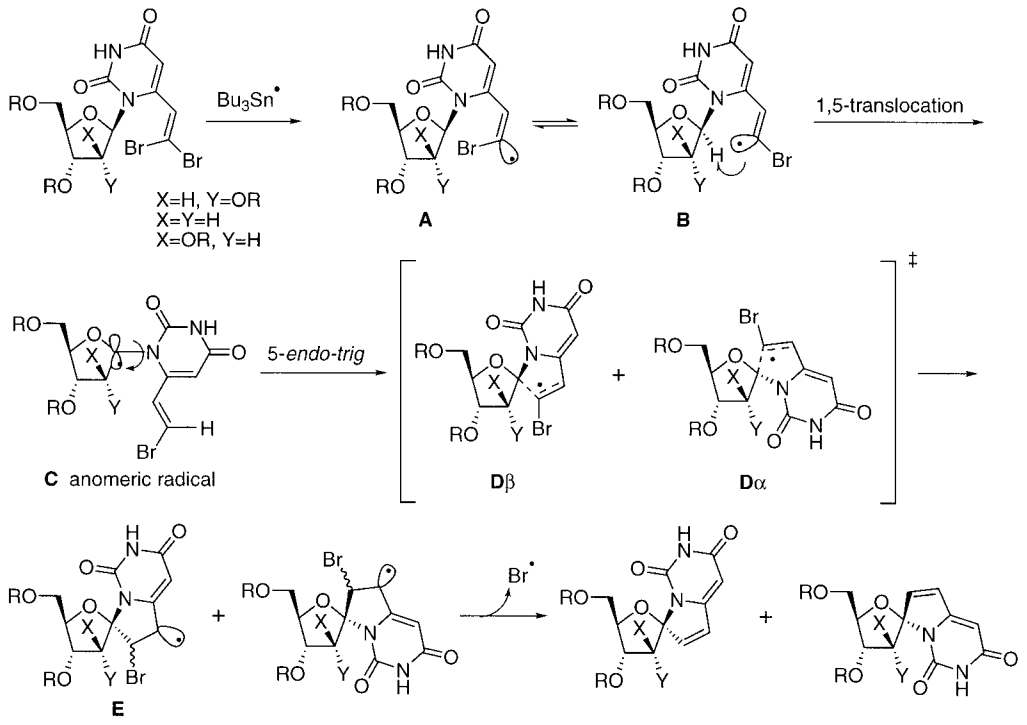
(22) Yamazaki, N.; Eichenberger, E.; Curran, D. P. *Tetrahedron Lett.* **1994**, *35*, 6623−6626.

(23) N3-anisotropic effect was considered in analysis of syn and anti conformations of base moiety of purine nucleosides: (a) Dudycz, L.; Stolarski, R.; Pless, R.; Shugar, D. *Naturforsch.* **1979**, *34c*, 359−373. (b) Evans, F. E.; Kaplan, N. O. *J. Biol. Chem.* **1976**, *251*, 6791−6797.

(24) It is known that heteroatoms raise the energy barrier to inversion of vinyl radicals: (a) Jaspers, C. P.; Curran, D. P. *J. Am. Chem. Soc.* **1990**, *112*, 5601−5609. (b) Galli, C.; Guarnieri A.; Koch, H.; Mencarelli, P.; Rappoport, Z. *J. Org. Chem.* **1997**, *62*, 4072−4077.

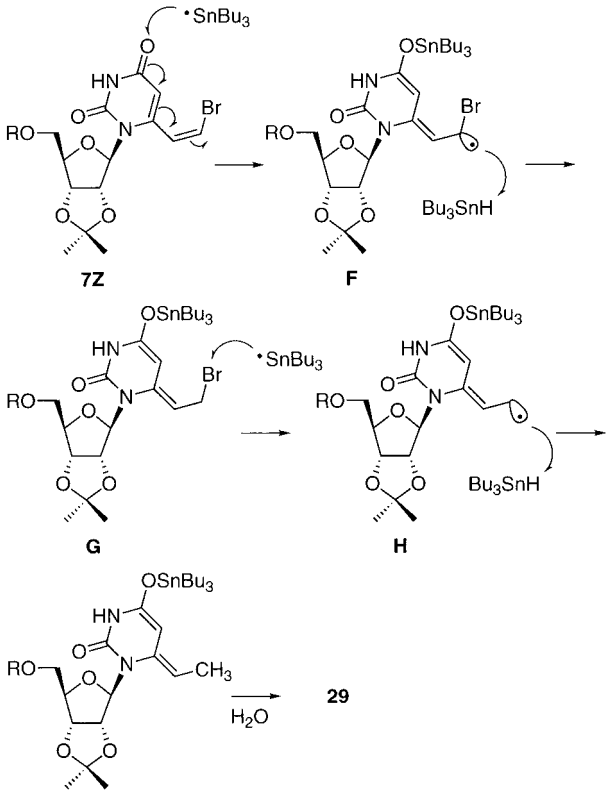
(25) Recently Chatgilialoglu et al. reported the slight pyramidal structure of **C** by spectroscopical and computational study in ref 6.

Scheme 7



It has been well accepted in synthetic chemistry that once vinyl radical is formed, equilibrium between (*E*)- and (*Z*)-isomers is very fast;[28] therefore, it is not necessary to distinguish the (*E*)- and (*Z*)-configuration of the starting halogenoolefins.[29] In our results, monoiodoolefins **8E** and **8Z** gave the same spiro compound in the same efficacy (~77%) as expected; however, monobromoolefins **7E** and **7Z** afforded completely different compounds. Since the (*E*)-bromoolefin underwent cyclization (31%) but the (*Z*)-bromoolefin did not, the rate of attack by tin radical at the hindered bromine atom of (*Z*)-bromoolefin **7Z** should be extremely slow. Instead, the C4-carbonyl oxygen would be attacked by tin radical to form allylic *O*-stannyl ketyl[30] whose resonance structure is a tin enolate conjugating with allylic radical **F**, and the resulting C8 carbon radical is trapped by tin hydride. The bromine atom at the sp^3 carbon (C8) is now ready to be reduced by tin radical, because a steric disadvantage is solved and a stable allylic radical **H** is formed (Scheme 8). Hydrogen abstraction affords tin enolate, which is hydrolyzed during workup to give the (*E*)-6-ethylidene compound **29**.[31]

Scheme 8



Conclusions

We have studied in detail the nucleoside anomeric radical generation via the 1,5-translocation strategy and the following radical 5-*endo-trig* cyclization reaction

(26) Lin, T.-S.; Yang, J.-H.; Lin, M.-C.; Zhu, J.-L. *Tetrahedron Lett.* **1990**, *31*, 3829−3832.

(27) 2′,3′,5′-Tris-*O*-(TBDMS)-6-(2-iodo-2-phenylvinyl)uridine, not entirely a pure form, was synthesized from a 6-phenylethynyluridine derivative [Stille coupling of *O*-protected 6-iodouridine with phenylethynyl(tributyl)tin (1.85 equiv) in the presence of 10 mol % $PdCl_2(CH_3CN)_2$ in THF, rt, 94%] via nonregioselective hydrostanylation [1 mol % $PdCl_2(CH_3CN)_2$, Bu_3SnH (3 equiv), THF, rt, 46%] followed by a stannane−iodine exchange reaction [I_2 (1 equiv), THF, rt, quant]. The radical reaction of this compound gave **17**β and **17**α in 23% and 6% yields, respectively.

(28) Jenkins, P. R.; Symons, M. C. R.; Booth, S. E.; Swain, C. J. *Tetrahedron Lett.* **1992**, *33*, 3543−3546.

(29) (a) Stork, G.; Baine, N. H. *J. Am. Chem. Soc.* **1982**, *104*, 2321−2323. (b) Curran, D. P.; Kuo, S.-C. *J. Am. Chem. Soc.* **1986**, *108*, 1106−1107. (c) Curran, D. P.; Kuo, S.-C. *Tetrahedron* **1987**, *43*, 5653−5661. (d) Meyers, A. I.; Lefker, B. A. *Tetrahedron* **1987**, *43*, 5663−5676.

(30) Enholm, E. J.; Whitley, P. E. *Tetrahedron Lett.* **1995**, *36*, 9157−9160.

(31) Although it is not clear why only (*E*)-isomer **29** was obtained, free rotation around the C6−C7 bond of **7Z** is probably restricted by steric repulsion between the (*Z*)-bromovinyl group and the sugar portion.

toward olefin tethered on base moiety to produce spiro nucleosides. The energy barrier of the transition states of cyclization that control the face selectivity seems to be caused by interaction between the C2-carbonyl group and the 2′-substituent. The hindered (*Z*)-bromo group were hardly attacked by tin radical and afforded unstable nucleoside derivative **29**, which was isolated for the first time. Both 2′-deoxyuridine and α-2′-deoxyuridine derivatives gave the same 6,1′-etheno-bridged compounds in the same ratio. The nucleoside anomeric radical intermediate should have a planar structure, and the C1′-N1 bond rotation is much faster than the 5-*endo*-*trig* cyclization process. These findings should provide a better understanding of nucleoside anomeric radicals and the chemistry of nucleosides.

Experimental Section

General Information. Melting points are uncorrected. ^{1}H NMR spectra were measured at 23 °C (internal standard, Me_4-Si) at either 400 or 500 MHz. Mass spectra (MS) were taken in a FAB mode (*m*-nitrobenzyl alcohol as a matrix). A commercially available hexane solution of BuLi was titrated before use with diphenyl acetic acid in THF.[32] THF was distilled from benzophenone ketyl. Column chromatography was carried out on silica gel (Silica Gel 60, Merck). Thin-layer chromatography (TLC) was performed on silica gel (precoated silica gel plate F_{254}, Merck). Preparative HPLC was carried out on a Shimpack PREP-SIL(H)·KIT column (2 × 25 cm).

6-(2,2-Dibromovinyl)-5′-*O*-(*tert*-butyldimethylsilyl)-2′,3′-*O*-isopropylideneuridine (1a). To a THF (47 mL) solution of LDA (28.4 mmol) was added 5′-*O*-(*tert*-butyldimethylsilyl)-2′,3′-*O*-isopropylideneuridine (3.78 g, 9.48 mmol) in THF (47 mL) via a syringe while the temperature was maintained below −70 °C. After the mixture was stirred for 30 min at −78 °C, DMF (8.08 mL, 104.3 mmol) was added, and the mixture was stirred for 30 min at the same temperature. The reaction mixture was treated with AcOH (5.43 mL, 94.8 mmol), diluted with EtOAc (500 mL), and washed with water (100 mL). The organic layer was separated and washed with saturated aqueous $NaHCO_3$, H_2O, and brine (100 mL each), successively, and dried over Na_2SO_4. Partial purification by short column chromatography on silica gel (50% EtOAc in hexane) gave crude aldehyde (3.92 g) as a pale yellow foam, which was used for the Wittig reaction without further purification. Aldehyde in DMF (48 mL) was added at 0 °C to a solution of dibromomethylene triphenylphosphorane in CH_2Cl_2, prepared according to the published procedure[10] [Zn powder (1.55 g, 23.7 mmol), Ph_3P (6.22 g, 23.7 mmol), and CBr_4 (7.86 g, 23.7 mmol) in CH_2Cl_2 (46.6 mL), overnight at room temperature], and the mixture was stirred for 2 h at room temperature. The mixture was diluted with EtOAc (500 mL) and washed successively with H_2O, saturated aqueous $NaHCO_3$, H_2O, and brine (100 mL each). The organic layer was dried over Na_2SO_4, evaporated to dryness, and chromatographed on silica gel (10−33% EtOAc in hexane) to afford **1a** (3.57 g, 65%, based on the starting material) as a colorless oil: $[\alpha]^{23}_D = -9.4$ (*c* 0.2, $CHCl_3$); UV (MeOH) λ_{max} 275 nm (ϵ 8600), λ_{min} 247 nm (ϵ 6000); ^{1}H NMR ($CDCl_3$) δ 8.86 (1H, br), 7.23 (1H, d, J = 1.1 Hz), 5.82 (1H, br), 5.68 (1H, d, J = 1.1 Hz), 5.15 (1H, dd, J = 1.5, 6.4 Hz), 4.80 (1H, dd, J = 4.4, 6.4 Hz), 4.13 (1H, ddd, J = 4.4, 5.1, 7.3 Hz), 3.82 (1H, dd, J = 5.1, 11.0 Hz), 3.78 (1H, dd, J = 7.3, 11.0 Hz), 1.56 and 1.35 (6H, each as s), 0.89 (9H, s), 0.05 (6H, s); FAB MS *m*/*z* 585, 583, and 581 $(M + H)^+$, 569, 567, and 565 $(M - Me)^+$, 527, 525, and 523 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{30}Br_2N_2O_6Si$: C, 41.25; H, 5.19; N, 4.81. Found: C, 41.47; H, 5.15; N, 4.69.

2′,3′,5′-Tris-*O*-(*tert*-butyldimethylsilyl)-6-(2,2-dibromovinyl)uridine (1b). Dibromoolefin **1a** (422.5 mg, 0.725 mmol) was dissolved in 50% aqueous CF_3COOH (15 mL), and the solution was stirred for 1.5 h at room temperature. The solvents were coevaporated with EtOH and toluene (10 mL each), and the residue was purified by silica gel column chromatography (1−9% MeOH in CH_2Cl_2) to yield free 6-(2,2-dibromovinyl)uridine (291.1 mg, 94%) as a white powder, which was used without further purification for preparation of **1b** and **1c**. 6-(2,2-Dibromovinyl)uridine: ^{1}H NMR (DMSO-d_6) δ 11.59 (1H, br, D_2O exchangeable), 7.63 (1H, d, J = 1.1 Hz), 5.70 (1H, dd, J = 1.1, 2.2 Hz), 5.64 (1H, d, J = 4.8 Hz), 5.31 (1H, d, J = 5.9 Hz, D_2O exchangeable), 5.05 (1H, d, J = 6.6 Hz, D_2O exchangeable), 4.83 (1H, t, J = 4.8 Hz, D_2O exchangeable), 4.25 (1H, dd, J = 4.8, 6.6 Hz), 3.99 (1H, dd, J = 6.2, 6.6 Hz), 3.68∼3.61 (2H, m), 3.47 (1H, dd, J = 4.8, 11.7 Hz); FAB MS *m*/*z* 431, 429, and 427 $(M + H)^+$.

6-(2,2-Dibromovinyl)uridine (819.0 mg, 1.28 mmol) was dissolved in DMF (10 mL), and imidazole (610.0 mg, 8.96 mmol) and TBDMSCl (964.7 mg, 6.40 mmol) were added. The mixture was stirred overnight at room temperature and partitioned between EtOAc (100 mL) and H_2O (30 mL). The organic layer was separated, washed with H_2O and brine (30 mL each), dried (Na_2SO_4), and concentrated. Silica gel column chromatography (10−14% EtOAc in hexane) gave **1b** (722.3 mg, 73%) as a colorless oil: $[\alpha]^{23}_D = -42.0$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 277 nm (ϵ 8400), λ_{min} 248 nm (ϵ 6200); ^{1}H NMR ($CDCl_3$) δ 8.28 (1H, br), 7.18 (1H, d, J = 1.1 Hz), 5.83 (1H, t, J = 1.1 Hz), 5.48 (1H, d, J = 5.9 Hz), 4.97 (1H, dd, J = 4.4, 5.9 Hz), 4.27 (1H, dd, J = 3.3, 4.4 Hz), 3.90 (1H, ddd, J = 3.3, 4.8, 7.3 Hz), 3.79 (1H, dd, J = 7.3, 11.0 Hz), 3.68 (1H, dd, J = 4.8, 11.0 Hz), 0.91, 0.89 and 0.88 (27H, each as s), 0.10, 0.06 and −0.01 (18H, each as s); FAB MS *m*/*z* 773, 771 and 769 $(M + H)^+$, 715, 713, and 711 $(M - {}^tBu)^+$. Anal. Calcd for $C_{29}H_{54}Br_2N_2O_6Si_3$: C, 45.19; H, 7.06; N, 3.63. Found: C, 45.42; H, 7.07; N, 3.48.

6-(2,2-Dibromovinyl)-2′,3′,5′-tri-*O*-acetyluridine (1c). 6-(2,2-Dibromovinyl)uridine (458.0 mg, 1.07 mmol) was dissolved in pyridine (5.4 mL), and Ac_2O (0.608 mL, 6.42 mmol) was added. The solution was stirred for 5 h at room temperature and concentrated. The residue was partitioned between EtOAc (150 mL) and H_2O (50 mL), and the organic layer was washed with brine (50 mL) and dried over Na_2SO_4. Purification by column chromatography on silica gel (10−50% EtOAc in hexane) gave **1c** (489.1 mg, 83%) as an oil: $[\alpha]^{23}_D = +62.1$ (*c* 0.15, $CHCl_3$); UV (MeOH) λ_{max} 272 nm (ϵ 8300), λ_{min} 246 nm (ϵ 5800); ^{1}H NMR ($CDCl_3$) δ 8.55 (1H, br), 7.16 (1H, d, J = 1.1 Hz), 5.79 (1H, dd, J = 1.1, 1.5 Hz), 5.67 (1H, dd, J = 2.9, 7.0 Hz), 5.53 (1H, d, J = 2.9 Hz), 5.49 (1H, dd, J = 7.0, 7.7 Hz), 4.47 (1H, m), 4.27∼4.21 (2H, m), 2.12 and 2.11 (9H, each as s); FAB MS *m*/*z* 557, 555, and 553 $(M + H)^+$, 497, 495, and 493 $(M - OAc)^+$. Anal. Calcd for $C_{17}H_{18}Br_2N_2O_9$: C, 36.85; H, 3.27; N, 5.06. Found: C, 36.95; H, 3.04; N, 4.75.

6-(2,2-Dibromovinyl)-3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-2′-deoxyuridine (2). 3′,5′-*O*-(Tetraisopropyldisiloxan-1,3-diyl)-2′-deoxyuridine (852.0 mg, 1.81 mmol) was treated by the procedure described for the formylation and the Wittig reaction for the synthesis of **1a**. Formylation underwent in ca. 58% yield along with 46% recovery of the starting material (390.5 mg). The following Wittig reaction for the crude aldehyde (453.3 mg, ca. 0.909 mmol) gave **2** (436.2 mg, 73%) after silica gel column chromatography (10−33% EtOAc in hexane) as a wax: UV (MeOH) λ_{max} 278 nm (ϵ 6100), λ_{min} 249 nm (ϵ 4200); ^{1}H NMR ($CDCl_3$) δ 8.40 (1H, br), 7.22 (1H, d, J = 1.3 Hz), 5.98 (1H, dd, J = 4.4, 9.2 Hz), 5.74 (1H, dd, J = 1.3, 2.2 Hz), 4.83 (1H, ddd, J = 6.2, 6.6, 8.8 Hz), 4.04 (1H, dd, J = 3.7, 11.4 Hz), 3.96 (1H, dd, J = 7.9, 11.4 Hz), 3.79 (1H, ddd, J = 3.7, 6.6, 7.9 Hz), 2.76 (1H, ddd, J = 4.4, 8.8, 13.9 Hz), 2.37 (1H, ddd, J = 6.2, 9.2, 13.9 Hz), 1.17∼0.99 (28H, m, TIPDS); FAB MS *m*/*z* 657, 655, and 653 $(M + H)^+$, 613, 611, and 609 $(M - {}^iPr)^+$. Anal. Calcd for $C_{23}H_{38}Br_2N_2O_6$: C, 42.21; H, 5.85; N, 4.28. Found: C, 42.53; H, 5.82; N, 4.26.

1-[2,3,5-Tris-*O*-(*tert*-butyldimethylsilyl)-β-D-arabinofuranosyl]-6-(2,2-dibromovinyl)-4-ethoxy-2-pyrimidinone (3). 1-[2,3,5-Tris-*O*-(*tert*-butyldimethylsilyl)-β-D-arabinofuranosyl]-4-ethoxy-2-pyrimidinone (847.4 mg, 1.38 mmol) was treated by the procedure described for the formylation and the Wittig reaction of **1a**. Formylation afforded crude aldehyde

(32) Kofron, W. G.; Baclawski, L. M. *J. Org. Chem.* **1976**, *41*, 1879−1880.

(617.0 mg, ca. 70%) along with 22% recovery of the starting material (188.3 mg). The following Wittig reaction for the crude aldehyde (220.9 mg, ca. 0.344 mmol) gave **3** (235.0 mg, 86%), after silica gel column chromatography (10−17% EtOAc in hexane), as an oil: UV (MeOH) λ_{max} 305 nm (ϵ 8700), λ_{min} 277 nm (ϵ 5200); ^{1}H NMR ($CDCl_3$) δ 7.58 (1H, d, J = 0.9 Hz), 6.24 (1H, d, J = 2.6 Hz), 5.98 (1H, d, J = 0.9 Hz), 4.42 and 4.41 (2H, each as dq, J = 7.1, 14.3 Hz), 4.35 (1H, d, J = 2.6 Hz), 4.18 (1H, s), 3.94 (1H, dd, J = 4.8, 8.1 Hz), 3.90 (1H, dd, J = 4.8, 9.5 Hz), 3.77 (1H, dd, J = 8.1, 9.5 Hz), 1.35 (3H, t, J = 7.1 Hz), 0.91, 0.90 and 0.82 (27H, each as s), 0.13, 0.11, 0.09, 0.07 and −0.15 (18H, each as s); FAB MS *m/z* 823, 821, and 819 $(M + Na)^+$, 801, 799, and 797 $(M + H)^+$, 785, 783, and 781 $(M - Me)^+$, 743, 741, and 739 $(M - {}^tBu)^+$. Anal. Calcd for $C_{31}H_{58}Br_2N_2O_6Si_3$: C, 46.61; H, 7.32; N, 3.51. Found: C, 46.96; H, 7.40; N, 3.48.

3′,5′-Bis-*O*-(*tert*-butyldimethylsilyl)-6-(2,2-dibromovinyl)spongouridine (4a). Compound **3** (413.5 mg, 0.518 mmol) was dissolved in MeOH (20 mL), and 1 M HCl (6.7 mL) was added dropwise. The suspension was stirred at room temperature overnight, and an additional 3 mL of 1 M HCl was added to the resulting solution. After being stirred for 5 h, the solution was concentrated, and the residue was purified by silica gel column chromatography (2−8% MeOH in CH_2Cl_2) to give 6-(2,2-dibromovinyl)spongouridine (236.2 mg, quant) as a pale yellow powder, which was used without further purification for the preparation of **4a** and **4b**. 6-(2,2-Dibromovinyl)spongouridine: ^{1}H NMR (DMSO-d_6) δ 11.53 (1H, br), 7.64 (1H, d, J = 1.1 Hz), 6.12 (1H, d, J = 5.5 Hz), 5.72 (1H, d, J = 4.4 Hz, D_2O exchangeable), 5.62 (1H, t, J = 1.1 Hz), 5.44 (1H, d, J = 5.1 Hz, D_2O exchangeable), 4.86 (1H, t, J = 5.3 Hz, D_2O exchangeable), 4.05 (1H, dd, J = 4.0, 5.5 Hz), 3.83 (1H, dd, J = 4.0, 5.9 Hz), 3.62 and 3.60 (2H, each as dd, J = 4.9, 11.6 Hz), 3.55 (1H, dt, J = 4.9, 5.9 Hz); FAB MS *m/z* 431, 429, and 427 $(M + H)^+$.

A mixture of 6-(2,2-dibromovinyl)spongouridine (61.1 mg, 0.143 mmol), imidazole (97.4 mg, 1.43 mmol), and TBDMSCl (107.8 mg, 0.715 mmol) in DMF (5 mL) was stirred at room temperature for 4 days. Conventional workup followed by silica gel column chromatography (10−33% EtOAc in hexane) gave **4a** (52.8 mg, 56%) as a solid that was analytically pure: mp 140−144 °C; $[\alpha]^{23}_D$ = +7.5 (*c* 0.4, $CHCl_3$); UV (MeOH) λ_{max} 288 nm (ϵ 8900), λ_{min} 250 nm (ϵ 5600); ^{1}H NMR ($CDCl_3$) δ 8.61 (1H, br), 7.35 (1H, d, J = 1.1 Hz), 5.97 (1H, d, J = 5.1 Hz), 5.77 (1H, t, J = 1.1 Hz), 4.24 (1H, ddd, J = 3.7, 5.1, 9.2 Hz), 4.19 (1H, t, J = 3.7 Hz), 3.92∼3.81 (3H, m), 3.53 (1H, d, J = 9.2 Hz), 0.92 and 0.90 (18H, each as s), 0.14, 0.12, and 0.11 (12H, each as s); FAB MS *m/z* 681, 679, and 677 $(M + Na)^+$, 659, 657, and 655 $(M + H)^+$, 601, 599, and 597 $(M - {}^tBu)^+$. Anal. Calcd for $C_{23}H_{40}Br_2N_2O_6Si_2$: C, 42.08; H, 6.14; N, 4.27. Found: C, 41.99; H, 6.05; N, 4.12.

2′,3′,5′-Tri-*O*-acetyl-6-(2,2-dibromovinyl)spongouridine (4b). A mixture of 6-(2,2-dibromovinyl)spongouridine (318.1 mg, 0.743 mmol) and Ac_2O (0.422 mL, 4.46 mmol) in pyridine (7 mL) was stirred at room temperature for 10 h. The pale brown solution was concentrated with EtOH and toluene (10 mL each), and the residue was partitioned between EtOAc (80 mL) and H_2O (10 mL). The organic layer was washed successively with 1 M HCl, saturated aqueous $NaHCO_3$, H_2O, and brine (15 mL each), dried (Na_2SO_4), and concentrated. The residue was purified by silica gel column (10−40%EtOAc in hexane) to yield **4b** (332.2 mg, 81%) as a white foam: $[\alpha]^{24}_D$ = −45.2 (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 274 nm (ϵ 8100), λ_{min} 248 nm (ϵ 5700); ^{1}H NMR ($CDCl_3$) δ 9.25 (1H, br), 7.24 (1H, br), 6.07 (1H, d, J = 7.3 Hz), 5.79 (1H, dd, J = 6.2, 7.3 Hz), 5.76 (1H, br), 5.40 (1H, dd, J = 6.2, 7.3 Hz), 4.53 (1H, dd, J = 2.9, 12.1 Hz), 4.39 (1H, dd, J = 8.1, 12.1 Hz), 4.09 (1H, ddd, J = 2.9, 7.3, 8.1 Hz), 2.10, 2.08 and 2.06 (9H, each as s); FAB MS *m/z* 557, 555, and 553 $(M + H)^+$. Anal. Calcd for $C_{17}H_{18}Br_2N_2O_9$: C, 36.85; H, 3.27; N, 5.06. Found: C, 37.21; H, 3.29; N, 4.79.

5′-*O*-(*tert*-Butyldimethylsilyl)-6-ethynyl-2′,3′-*O*-isopropylideneuridine (5). Compound **1a** (687.2 mg, 1.18 mmol) was dissolved in THF (11.8 mL) and treated with a hexane solution of BuLi (3.54 mmol) at −78 °C. The reaction mixture was stirred for 5 min and quenched with AcOH (0.270 mL, 4.72 mmol). After extractive workup between EtOAc (50 mL) and saturated aqueous NH_4Cl (20 mL), the organic layer was washed with H_2O and brine (20 mL each). After drying with Na_2SO_4, purification of the mixture by silica gel column chromatography (9−40% EtOAc in hexane) gave **5** (412.8 mg, 83%) as an oil: UV (MeOH) λ_{max} 283 nm (ϵ 10000), λ_{min} 244 nm (ϵ 2200); ^{1}H NMR ($CDCl_3$) δ 8.97 (1H, br), 6.26 (1H, d, J = 1.5 Hz), 6.02 (1H, d, J = 2.2 Hz), 5.19 (1H, dd, J = 1.5, 6.6 Hz), 4.82 (1H, dd, J = 4.6, 6.6 Hz), 4.16 (1H, m), 3.81∼3.79 (2H, m), 3.78 (1H, s), 1.55 and 1.34 (6H, each as s), 0.89 (9H, s), 0.05 (6H, s); FAB MS *m/z* 445 $(M + Na)^+$, 423 $(M + H)^+$, 407 $(M - Me)^+$, and 365 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{30}N_2O_6Si$: C, 56.85; H, 7.16; N, 6.63. Found: C, 56.64; H, 7.36; N, 6.43.

Hydrostannylation of 6-Ethynyluridine 5. The mixture of **5** (990.9 mg, 2.35 mmol), Bu_3SnH (1.26 mL, 4.69 mmol), and AIBN (192.5 mg, 1.17 mmol) in benzene (47 mL) was refluxed for 1 h. The whole reaction mixture was applied to a silica gel column. Elution with 9−12% EtOAc in hexane gave a fraction of a mixture of *trans*- and *cis*-stannylolefins (461.1 mg) and a pure fraction of *trans*-olefin **6E** (444.7 mg). The former fraction was rechromatographed on silica gel with the same solvent system to give the *cis*-olefin **6Z** (110.6 mg, 6.6%) and the *trans*-olefin **6E** (279.8 mg, total 724.5 mg, 43.5%). Physical data of these compounds are as follows:

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6-[(*E*)-2-(tributylstannyl)vinyl]uridine (6E). This compound was obtained as an oil: UV (MeOH) λ_{max} 281 nm (ϵ 10900), λ_{min} 248 nm (ϵ 7300); ^{1}H NMR ($CDCl_3$) δ 8.62 (1H, br), 7.09 (1H, d, J = 19.2 Hz, J ^{1}H-^{117}Sn = 54.6, J ^{1}H-^{119}Sn = 57.1 Hz), 6.67 (1H, d, J = 19.2 Hz, J ^{1}H-^{117}Sn = J ^{1}H-^{119}Sn = 52.6 Hz), 5.72 (1H, s), 5.66 (1H, d, J = 1.5 Hz), 5.22 (1H, dd, J = 1.5, 6.4 Hz), 4.82 (1H, dd, J = 4.3, 6.4 Hz), 4.16 (1H, ddd, J = 4.3, 5.5, 7.0 Hz), 3.82 (1H, dd, J = 5.5, 11.0 Hz), 3.79 (1H, dd, J = 7.0, 11.0 Hz), 1.58∼1.50 (6H, m), 1.51 and 1.33 (6H, each as s), 1.36∼1.30 (6H, m), 1.02∼0.99 (6H, m), 0.92∼0.90 (9H, m), 0.89 (9H, s), 0.05 (6H, s); FAB MS *m/z* 715, 713, and 711 $(M + H)^+$, 657, 655, and 653 $(M - {}^tBu)^+$. Anal. Calcd for $C_{32}H_{58}N_2O_6SiSn$: C, 53.86; H, 8.19; N, 3.93. Found: C, 54.18; H, 8.15; N, 3.84.

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6-[(*Z*)-2-(tributylstannyl)vinyl]uridine (6Z). This compound was obtained as an oil: UV (MeOH) λ_{max} 268 nm (ϵ 7800), λ_{min} 240 nm (ϵ 5100); ^{1}H NMR ($CDCl_3$) δ 8.75 (1H, br), 7.20 (1H, d, J = 14.0 Hz, J ^{1}H-^{117}Sn = 105.0, J ^{1}H-^{119}Sn = 109.2 Hz), 6.72 (1H, d, J = 14.0 Hz, J ^{1}H-^{117}Sn = 48.8, J ^{1}H-^{119}Sn = 50.8 Hz), 5.78 (1H, br), 5.54 (1H, d, J = 1.4 Hz), 5.15 (1H, dd, J = 1.4, 6.4 Hz), 4.82 (1H, dd, J = 4.3, 6.4 Hz), 4.10 (1H, ddd, J = 4.3, 5.2, 7.0 Hz), 3.81 (1H, dd, J = 5.2, 10.7 Hz), 3.77 (1H, dd, J = 7.0, 10.7 Hz), 1.52 and 1.31 (6H, each as s), 1.50∼1.43 (6H, m), 1.32∼1.25 (6H, m), 0.96∼0.93 (6H, m), 0.89∼0.87 (9H, m), 0.89 (9H, s), 0.05 (6H, s); FAB MS *m/z* 715, 713, and 711 $(M + H)^+$, 699, 697, and 695 $(M - Me)^+$, 657, 655, and 653 $(M - {}^tBu)^+$. Anal. Calcd for $C_{32}H_{58}N_2O_6SiSn$: C, 53.86; H, 8.19; N, 3.93. Found: C, 53.75; H, 8.09; N, 3.86.

6-[(*E*)-2-Bromovinyl]-5′-*O*-(*tert*-butyldimethylsilyl)-2′,3′-*O*-isopropylideneuridine (7E). To the THF (9.9 mL) solution of **6E** (197.0 mg, 0.276 mmol) was added NBS (98.2 mg, 0.552 mmol) at room temperature, and the mixture was stirred for 30 min. The mixture was diluted with EtOAc (100 mL), washed successively with 0.2 M $Na_2S_2O_3$, saturated aqueous $NaHCO_3$, H_2O, and brine (30 mL each), dried (Na_2SO_4), and concentrated. Purification on a silica gel column (10−20% EtOAc in hexane) gave **7E** (135.0 mg, 97%) as a foam: UV (MeOH) λ_{max} 279 nm (ϵ 9100), λ_{min} 257 nm (ϵ 6800), $\lambda_{shoulder}$ 242 nm (ϵ 8200); ^{1}H NMR ($CDCl_3$) δ 9.09 (1H, br), 7.04 and 7.01 (2H, each as d, J = 17.1 Hz), 5.69 (1H, d, J = 1.7 Hz), 5.67 (1H, d, J = 1.2 Hz), 5.18 (1H, dd, J = 1.7, 6.4 Hz), 4.82 (1H, dd, J = 4.7, 6.4 Hz), 4.13 (1H, dt, J = 4.7, 7.0 Hz), 3.82 (1H, dd, J = 4.7, 11.0 Hz), 3.78 (1H, dd, J = 7.0, 11.0 Hz), 1.55 and 1.33 (6H, each as s), 0.89 (9H, s), 0.06 (6H, s); FAB MS *m/z* 505 and 503 $(M + H)^+$, 447 and 445 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{31}BrN_2O_6Si$: C, 47.71; H, 6.21; N, 5.56. Found: C, 47.45; H, 6.20; N, 5.40.

6-[(*Z*)-2-Bromovinyl]-5′-*O*-(*tert*-butyldimethylsilyl)-2′,3′-*O*-isopropylideneuridine (7Z). To a mixture of **1a** (362.6 mg, 0.623 mmol) and $Pd(PPh_3)_4$ (28.8 mg, 24.9 μmol) in benzene (7 mL) was added a solution of Bu_3SnH (0.335 mL, 1.25 mmol) in benzene (3 mL) at room temperature dropwise over 3 h using a syringe pump. The whole reaction mixture was applied to a silica gel column and eluted with 10−40% EtOAc in hexane to afford recovered **1a** (110.1 mg, 30%), 6-ethyluridine **30** (20.8 mg, 7.8%), 6-vinyluridine (13.2 mg, 5.0%), and the title compound **7Z** (126.5 mg, 40%) as a colorless oil: UV (MeOH) λ_{max} 271 nm (ϵ 7700), λ_{min} 243 nm (ϵ 5200); ^{1}H NMR ($CDCl_3$) δ 8.85 (1H, br), 6.99 and 6.90 (2H, each as d, J = 8.2 Hz), 5.86 (1H, br), 5.72 (1H, br), 5.15 (1H, dd, J = 1.3, 6.2 Hz), 4.81 (1H, dd, J = 4.8, 6.2 Hz), 4.10 (1H, dt, J = 4.8, 6.6 Hz), 3.83 (1H, dd, J = 4.8, 11.0 Hz), 3.78 (1H, dd, J = 6.6, 11.0 Hz), 1.53 and 1.33 (6H, each as s), 0.89 (9H, s), 0.05 (6H, s); FAB MS m/z 527 and 525 $(M + Na)^+$, 505 and 503 $(M + H)^+$, 489 and 487 $(M - Me)^+$, 447 and 445 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{31}BrN_2O_6Si$: C, 47.71; H, 6.21; N, 5.56. Found: C, 47.36; H, 6.27; N, 5.54.

5′-*O*-(*tert*-Butyldimethylsilyl)-6-ethyl-2′,3′-*O*-isopropylideneuridine (30). This compound was obtained as a byproduct from Pd-catalyzed reduction of **1a** and also radical reaction of **7E** and **7Z** as an oil: UV (MeOH) λ_{max} 259 nm (ϵ 10600), λ_{min} 229 nm (ϵ 2400); ^{1}H NMR ($CDCl_3$) δ 8.64 (1H, br), 5.72 (1H, br), 5.58 (1H, d, J = 1.5 Hz), 5.19 (1H, dd, J = 1.5, 6.6 Hz), 4.81 (1H, dd, J = 4.8, 6.6 Hz), 4.13 (1H, dt J = 4.8, 7.1 Hz), 3.82 (1H, dd, J = 4.8, 11.0 Hz), 3.79 (1H, dd, J = 7.1, 11.0 Hz), 2.63 (2H, q, J = 7.3 Hz), 1.54 and 1.33 (6H, each as s), 1.28 (3H, t, J = 7.3 Hz), 0.88 (9H, s), 0.04 (6H, s); FAB MS m/z 449 $(M + Na)^+$, 427 $(M + H)^+$, 411 $(M - Me)^+$, and 369 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{34}N_2O_6Si$: C, 56.31; H, 8.03; N, 6.57. Found: C, 56.07; H, 8.25; N, 6.46.

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6-vinyluridine. This compound was obtained as a byproduct from Pd-catalyzed reduction of **1a** as an oil: UV (MeOH) λ_{max} 267 nm (ϵ 10700), λ_{min} 239 nm (ϵ 5000); ^{1}H NMR ($CDCl_3$) δ 9.10 (1H, br), 6.66 (1H, dd, J = 11.0, 16.9 Hz), 5.87 (1H, d, J = 11.0 Hz), 5.76 (1H, br), 5.73 (1H, d, J = 1.7 Hz), 5.66 (1H, d, J = 16.9 Hz), 5.18 (1H, dd, J = 1.7, 6.6 Hz), 4.83 (1H, dd, J = 4.8, 6.6 Hz), 4.11 (1H, dt, J = 4.8, 6.6 Hz), 3.84 (1H, dd, J = 4.8, 11.0 Hz), 3.80 (1H, dd, J = 6.6, 11.0 Hz), 1.53 and 1.33 (6H, each as s), 0.88 (9H, s), 0.05 (6H, s); FAB MS m/z 447 $(M + Na)^+$, 425 $(M + H)^+$, 409 $(M - Me)^+$, and 367 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{32}N_2O_6Si \cdot {}^1/_2H_2O$: C, 55.40; H, 7.67; N, 6.46. Found: C, 55.63; H, 7.73; N, 6.15.

6-[(*E*)-2-Iodovinyl]-5′-*O*-(*tert*-butyldimethylsilyl)-2′,3′-*O*-isopropylideneuridine (8E). To the THF (6.2 mL) solution of **6E** (222.3 mg, 0.311 mmol) was added I_2 (102.6 mg, 0.404 mmol) at room temperature, and the mixture was stirred for 30 min. The mixture was diluted with EtOAc (100 mL) and washed successively with 0.2 M $Na_2S_2O_3$, saturated aqueous $NaHCO_3$, H_2O, and brine (30 mL each), dried (Na_2SO_4), and concentrated. Chromatography of the residue on silica gel (10−20% EtOAc in hexane) afforded **8E** (183.5 mg, quant) as an oil: UV (MeOH) λ_{max} 282 nm (ϵ 11100), λ_{min} 233 nm (ϵ 6800); ^{1}H NMR ($CDCl_3$) δ 8.56 (1H, br), 7.33 and 7.24 (2H, each as d, J = 14.7 Hz), 5.68 (1H, d, J = 0.9 Hz), 5.66 (1H, d, J = 1.4 Hz), 5.18 (1H, dd, J = 1.4, 6.4 Hz), 4.82 (1H, dd, J = 4.3, 6.4 Hz), 4.14 (1H, ddd, J = 4.3, 5.2, 7.0 Hz), 3.82 (1H, dd, J = 5.2, 11.0 Hz), 3.78 (1H, dd, J = 7.0, 11.0 Hz), 1.56 and 1.34 (6H, each as s), 0.89 (9H, s), 0.06 (6H, s); FAB MS m/z 589 $(M + K)^+$, 573 $(M + Na)^+$, 551 $(M + H)^+$, 535 $(M - Me)^+$, and 493 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{31}IN_2O_6Si \cdot {}^1/_3H_2O$: C, 43.16; H, 5.74; N, 5.03. Found: C, 43.22; H, 5.57; N, 4.90.

6-[(*Z*)-2-Iodovinyl]-5′-*O*-(*tert*-butyldimethylsilyl)-2′,3′-*O*-isopropylideneuridine (8Z). To the THF (10.0 mL) solution of **6Z** (153.1 mg, 0.215 mmol) was added I_2 (60.0 mg, 0.236 mmol) portionwise over 6.5 h at room temperature. After the mixture was stirred overnight, further I_2 (60.0 mg) was added, and the reaction continued overnight. The mixture was diluted with EtOAc (100 mL), washed successively with 0.2 M $Na_2S_2O_3$, saturated aqueous $NaHCO_3$, H_2O, and brine (50 mL each), dried (Na_2SO_4), and concentrated. Silica gel column chromatography (10−30% EtOAc in hexane) of the residue afforded **8Z** (77.5 mg, 66%) as an oil: UV (MeOH) λ_{max} 267 nm (ϵ 5500), λ_{min} 245 nm (ϵ 4600); ^{1}H NMR ($CDCl_3$) δ 9.25 (1H, br), 7.18 and 7.15 (2H, each as d, J = 9.0 Hz), 5.80 (1H, d, J = 1.5 Hz), 5.77 (1H, d, J = 1.2 Hz), 5.14 (1H, dd, J = 1.2, 6.4 Hz), 4.81 (1H, dd, J = 4.6, 6.4 Hz), 4.09 (1H, dt, J = 4.6, 6.7 Hz), 3.83 (1H, dd, J = 4.6, 11.0 Hz), 3.79 (1H, dd, J = 6.7, 11.0 Hz), 1.52 and 1.33 (6H, each as s), 0.88 (9H, s), 0.05 (6H, s); FAB MS m/z 573 $(M + Na)^+$, 551 $(M + H)^+$, 535 $(M - Me)^+$, and 493 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{31}IN_2O_6Si$: C, 43.64; H, 5.68; N, 5.09. Found: C, 43.74; H, 5.49; N, 4.95.

6-(2,2-Dibromovinyl)-3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-α-2′-deoxyuridine (9). α-2′-Deoxyuridine (374.9 mg, 1.64 mmol) was dissolved in DMF (32.8 mL), and imidazole (336.0 mg, 4.94 mmol) and TIPDSCl (0.63 mL, 1.97 mmol) were added. The mixture was stirred overnight at room temperature. Conventional workup followed by silica gel column chromatography (30% EtOAc in hexane) gave 3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-α-2′-deoxyuridine (654.3 mg, 85%) as a solid, which was analytically pure: UV (MeOH) λ_{max} 261 nm (ϵ 7200), λ_{min} 229 nm (ϵ 1300); ^{1}H NMR ($CDCl_3$) δ 8.64 (1H, br), 7.71 (1H, d, J = 7.9 Hz), 6.16 (1H, dd, J = 5.5, 6.3 Hz), 5.75 (1H, dd, J = 1.9, 7.9 Hz), 4.57 (1H, dt, J = 6.3, 7.6 Hz), 4.06∼4.01 (2H, m), 3.80 (1H,dd, J = 8.1, 12.5 Hz), 2.83 (1H, dt, J = 6.3, 14.0 Hz), 2.16 (1H, ddd, J = 5.5, 6.3, 14.0 Hz), 1.09∼1.01 (28H, m, TIPDS); FAB MS m/z 471 $(M + H)^+$. Anal. Calcd for $C_{21}H_{38}N_2O_6Si_2$: C, 53.59; H, 8.14; N, 5.95. Found: C, 53.73; H, 8.16; N, 5.90.

3′,5′-*O*-(Tetraisopropyldisiloxan-1,3-diyl)-α-2′-deoxyuridine (313.2 mg, 0.665 mmol) was treated by the procedure described for the formylation and the Wittig reaction of **1a** to yield **9** (116.0 mg, 27%) after silica gel column chromatography (10−30% EtOAc in hexane) as a white foam: UV (MeOH) λ_{max} 280 nm (ϵ 6500), λ_{min} 250 nm (ϵ 4200); ^{1}H NMR ($CDCl_3$) δ 8.64 (1H, br), 7.29 (1H, d, J = 1.1 Hz), 6.10 (1H, dd, J = 6.7, 9.7 Hz), 5.75 (1H, t, J = 1.1 Hz), 4.50 (1H, dt, J = 7.6, 9.7 Hz), 4.17 (1H, ddd, J = 3.4, 4.6, 7.6 Hz), 3.99 (1H,dd, J = 3.4, 12.5 Hz), 3.90 (1H, dd, J = 4.6, 12.5 Hz), 2.63 (1H, dt, J = 9.7, 12.5 Hz), 2.52 (1H, ddd, J = 6.7, 7.6, 12.5 Hz), 1.13∼1.10 (28H, m, TIPDS); FAB MS m/z 657, 655, and 653 $(M + H)^+$. Anal. Calcd for $C_{23}H_{38}Br_2N_2O_6Si_2$: C, 42.21; H, 5.85; N, 4.24. Found: C, 42.47; H, 5.76; N, 4.24.

9-[2,3,5-Tris-*O*-(*tert*-butyldimethylsilyl)-β-D-ribofuranosyl]-6-chloro-8-(2,2-dibromovinyl)purine (10). 9-[2,3,5-Tris-*O*-(*tert*-butyldimethylsilyl)-β-D-ribofuranosyl]-6-chloropurine (1.57 g, 2.49 mmol) was treated by the procedure[18c] described for the formylation and the Wittig reaction of **1a**. Formylation underwent in ca. 93% yield (1.56 g). The following Wittig reaction for the crude aldehyde (1.31 g, ca. 1.99 mmol) gave **10** (704.0 mg, 44%) as an oil, after silica gel column chromatography (2−5% EtO_2 in hexane). Physical data are as follows: UV (MeOH) λ_{max} 297 nm (ϵ 13900) and 241 nm (ϵ 11600), λ_{min} 260 nm (ϵ 6300) and 225 nm (ϵ 9300); ^{1}H NMR ($CDCl_3$) δ 8.70 (1H, s), 7.66 (1H, s), 5.88 (1H, d, J = 5.5 Hz), 5.23 (1H, dd, J = 4.0, 5.5 Hz), 4.54 (1H, t, J = 4.0 Hz), 4.09 (1H, ddd, J = 4.0, 4.4, 6.2 Hz), 3.93 (1H, dd, J = 6.2, 11.0 Hz), 3.74 (1H, dd, J = 4.4, 11.0 Hz), 0.97, 0.80 and 0.77 (27H, each as s), 0.17, 0.16, −0.04 and −0.37 (18H, each as s); FAB MS m/z 817, 815, 813, and 811 $(M + H)^+$, 759, 757, 755, and 753 $(M - {}^tBu)^+$. Anal. Calcd for $C_{30}H_{53}Br_2ClN_4O_4Si_3$: C, 44.30; H, 6.57; N, 6.89. Found: C, 44.52; H, 6.78; N, 6.85.

Radical Reaction of the 6-Halovinyluridine and 6-Chloro-8-dibromovinylnebularine Derivatives 1−4 and 7−10. A typical procedure is given below for the reaction of **1a**. To a refluxing solution of **1a** (359.3 mg, 0.617 mmol) in benzene (31 mL) was added a mixture of Bu_3SnH (0.33 mL, 1.23 mmol) and AIBN (50.7 mg, 0.309 mmol) in benzene (3 mL) dropwise over 3 h using a syringe pump. The whole reaction mixture was applied to a silica gel column. Elution with 9−75% EtOAc in hexane gave a mixture of cyclized products **11**β, **11**α, and **15**β. Each product was isolated by HPLC (50 or 66% EtOAc in hexane, 10 mL/min) with the following yield and retention time: **11**β (solid, 104.7 mg, 40%, 12.9 min with 50% EtOAc in hexane); **15**β (oil, 9.5 mg, 3.1%, 14.7 min with the same solvent); **11**α (solid, 6.7 mg, 2.6%, 13.1 min with 66% EtOAc in hexane).

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6,1′-ethenouridine (11*β*). This compound was recrystallized from hexane−EtOAc to give an analytical sample: mp 169.0−170.0 °C; $[\alpha]^{23}_D = -18.7$ (*c* 0.1, $CHCl_3$); UV(MeOH) λ_{max} 290 nm (ϵ 12000), λ_{min} 251 nm (ϵ 4200); ^{1}H NMR ($CDCl_3$) δ 8.48 (1H, br), 6.74 and 6.43 (2H, each as d, J = 5.9 Hz), 5.68 (1H, d, J = 1.8 Hz), 5.15 (1H, d, J = 6.2 Hz), 4.99 (1H, dd, J = 4.4, 6.2 Hz), 4.29 (1H, dt, J = 4.4, 6.2 Hz), 3.90 (2H, d, J = 6.2 Hz), 1.58 and 1.34 (6H, each as s), 0.88 (9H, s), 0.06 and 0.05 (6H, each as s); FAB MS *m*/*z* 445 (M + Na)$^+$, 423 (M + H)$^+$, 407 (M − Me)$^+$, and 365 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{20}H_{30}N_2O_6Si$: C, 56.85; H, 7.61; N, 6.63. Found: C, 56.64; H 7.23; N, 6.56.

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6,1′-etheno-α-uridine (11α). Recrystallization from hexane−EtOAc gave an analytical sample: mp 240.0−240.5 °C; UV(MeOH) λ_{max} 293 nm (ϵ 11700), λ_{min} 256 nm (ϵ 3400); ^{1}H NMR ($CDCl_3$) δ 7.86 (1H, br), 6.44 and 6.38 (2H, each as d, J = 5.9 Hz), 5.65 (1H, d, J = 1.8 Hz), 5.04 (1H, dd, J = 4.0, 7.9 Hz), 4.95 (1H, dt, J = 2.2, 4.0 Hz), 4.76 (1H, d, J = 7.9 Hz), 3.83 and 3.77 (2H, each as dd, J = 2.2, 11.7 Hz), 1.58 and 1.33 (6H, each as s), 0.92 (9H, s), 0.09 and 0.08 (6H, each as s); FAB MS *m*/*z* 423 (M + H)$^+$, 407 (M − Me)$^+$, and 365 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{20}H_{30}N_2O_6Si \cdot {}^1/_4H_2O$: C, 56.25; H, 7.20; N, 6.56. Found: C, 56.38; H, 7.11; N, 6.38.

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6,1′-[(1*R*)-1-phenylethano]uridine (15*β*). This compound was obtained as an oil: UV(MeOH) $\lambda_{shoulder}$ 295 nm (ϵ 800), λ_{max} 261 nm (ϵ 12600), λ_{min} 231 nm (ϵ 3200); ^{1}H NMR ($CDCl_3$) δ 8.38 (1H, br), 7.54∼7.49 (2H, m), 7.32∼7.27 (3H, m), 5.58 (1H, br), 5.34 (1H, d, J = 6.4 Hz), 4.77 (1H, t, J = 6.4 Hz), 3.89 (1H, m), 3.72 (2H, m), 3.44 (1H, m), 3.18∼3.15 (2H, m), 1.26 and 0.98 (6H, each as s), 0.89 (9H, s), 0.02 (6H, s); FAB MS *m*/*z* 501 (M + H)$^+$, 485 (M − Me)$^+$, and 443 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{26}H_{36}N_2O_6Si \cdot {}^1/_3H_2O$: C, 61.63; H, 7.29; N, 5.53. Found: C, 61.37; H, 7.51; N, 5.51.

Radical Reaction of 1b. Compound **1b** (375.5 mg, 0.487 mmol) was treated by the procedure described for the radical reaction of **1a**. The following four cyclized compounds were isolated:

2′,3′,5′-Tris-*O*-(*tert*-butyldimethylsilyl)-6,1′-ethenouridine (12*β*). HPLC (33% EtOAc in hexane, retention time of 12.9 min) purification gave **12***β* (149.1 mg, 50%) as a white solid. Recrystallization from hexane gave an analytical sample: mp 215.0−215.5 °C; UV (MeOH) λ_{max} 291 nm (ϵ 12400), λ_{min} 248 nm (ϵ 4300); ^{1}H NMR ($CDCl_3$) δ 7.95 (1H, br), 6.97 and 6.28 (2H, each as d, J = 5.9 Hz), 5.65 (1H, d, J = 1.5 Hz), 5.43 (1H, d, J = 4.8 Hz), 4.26 (1H, d, J = 4.8 Hz), 4.09 (1H, dd, J = 4.9, 10.4 Hz), 3.92 (1H, t, J = 10.4 Hz), 3.71 (1H, dd, J = 4.9, 10.4 Hz), 0.95, 0.91 and 0.79 (27H, each as s), 0.14, 0.11, 0.09, 0.08, 0.02 and −0.10 (18H, each as s); FAB MS *m*/*z* 611 (M + H)$^+$, 595 (M − Me)$^+$, and 553 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{29}H_{54}N_2O_6Si_3$: C, 57.01; H, 8.91; N, 4.58. Found: C, 56.77; H 9.05; N, 4.47.

2′,3′,5′-Tris-*O*-(*tert*-butyldimethylsilyl)-6,1′-ethanouridine (16*β*). HPLC (33% EtOAc in hexane, retention time of 17.1 min) purification gave **16***β* (12.5 mg, 4.2%) as a solid. Recrystallization from hexane−EtOAc gave an analytical sample: mp 215.0−216.0 °C; UV (MeOH) λ_{max} 263 nm (ϵ 11700), λ_{min} 231 nm (ϵ 2300); ^{1}H NMR ($CDCl_3$) δ 8.11 (1H, br), 5.52 (1H, d, J = 1.2 Hz), 5.45 (1H, d, J = 4.6 Hz), 4.13 (1H, d, J = 4.6 Hz), 3.97 (1H, dd, J = 4.9, 10.2 Hz), 3.81 (1H, t, J = 10.2 Hz), 3.65 (1H, dd, J = 4.9, 10.2 Hz), 2.98∼2.88 (2H, m), 2.77∼2.70 (1H, m), 2.09∼2.03 (1H, m), 0.92, 0.91 and 0.86 (27H, each as s), 0.11, 0.09, 0.08, 0.07, 0.06 and −0.06 (18H, each as s); FAB MS *m*/*z* 613 (M + H)$^+$, 597 (M − Me)$^+$, and 555 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{29}H_{56}N_2O_6Si_3$: C, 56.82; H, 9.21; N, 4.57. Found: C, 56.95; H, 9.32; N, 4.61.

2′,3′,5′-Tris-*O*-(*tert*-butyldimethylsilyl)-6,1′-[(1*R*)-1-phenylethano]uridine (17*β*). HPLC (33% EtOAc in hexane, retention time of 15.1 min) purification gave **17***β* (16.1 mg, 4.8%) as an oil: UV (MeOH) λ_{max} 264 nm (ϵ 12200), λ_{min} 232 nm (ϵ 2600); ^{1}H NMR ($CDCl_3$) δ 8.00 (1H, br), 7.28∼7.19 (5H, m), 5.64 (1H, br), 5.04 (1H, d, J = 4.9 Hz), 4.39 (1H, d, J = 8.7 Hz), 4.19 (1H, d, J = 4.9 Hz), 3.78 (1H, dd, J = 3.8, 10.4 Hz), 3.75 (1H, dd, J = 2.1, 10.4 Hz), 3.57 (1H, dd, J = 2.1, 3.8 Hz), 3.27 (1H, ddd, J = 1.8, 8.7, 17.6 Hz), 2.92 (1H, d, J = 17.6 Hz), 0.99, 0.94, and 0.87 (27H, each as s), 0.19, 0.17, 0.11, 0.03, 0.01 and −0.04 (18H, each as s); FAB MS *m*/*z* 711 (M + Na)$^+$, 689 (M + H)$^+$, 673 (M − Me)$^+$, and 631 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{35}H_{60}N_2O_6Si_3$: C, 61.00; H, 8.78; N, 4.07. Found: C, 60.90; H, 8.87; N, 4.00.

2′,3′,5′-Tris-*O*-(*tert*-butyldimethylsilyl)-6,1′-[(1*R*)-1-phenylethano]-α-uridine (17α). HPLC (50% EtOAc in hexane, retention time of 11.6 min) purification gave **17**α (10.4 mg, 3.1%) as an oil: UV (MeOH) λ_{max} 264 nm (ϵ 13500), λ_{min} 232 nm (ϵ 2200); ^{1}H NMR ($CDCl_3$) δ 7.68 (1H, br), 7.45∼7.38 (5H, m), 5.60 (1H, br), 4.61 (1H, ddd, J = 2.4, 4.6, 9.8 Hz), 3.95 (1H, dd, J = 2.4, 12.1 Hz), 3.73 (1H, dd, J = 7.3, 13.6 Hz), 3.69 (1H, d, J = 4.6 Hz), 3.64 (1H, dd, J = 4.6, 12.1 Hz), 3.10 (1H, ddd, J = 1.8, 13.6, 16.6 Hz), 2.98 (1H, dd, J = 7.3, 16.6 Hz), 2.86 (1H, dd, J = 4.6, 9.8 Hz), 0.96, 0.84 and 0.76 (27H, each as s), 0.16, 0.15, −0.01, −0.04, −0.26, and −0.32 (18H, each as s); FAB MS *m*/*z* 689 (M + H)$^+$, 673 (M − Me)$^+$, and 631 (M − ^{t}Bu)$^+$. Anal. Calcd for $C_{35}H_{60}N_2O_6Si_3$: C, 61.00; H, 8.78; N, 4.07. Found: C, 60.95; H, 8.97; N, 4.05.

Radical Reaction of 1c. Compound **1c** (188.8 mg, 0.341 mmol) was treated by the procedure described for the radical reaction of **1a**. The following six cyclized compounds were isolated:

2′,3′,5′-Tri-*O*-acetyl-6,1′-ethenouridine (13*β*). HPLC purification (75% EtOAc in hexane, retention time of 21.3 min) gave **13***β* (53.1 mg, 40%) as a solid. Recrystallization from hexane−EtOAc gave an analytical sample: mp 209.0−209.5 °C; $[\alpha]^{23}_D = -154.0$ (*c* 0.2, $CHCl_3$); UV (MeOH) λ_{max} 290 nm (ϵ 11400), λ_{min} 253 nm (ϵ 4100); ^{1}H NMR ($CDCl_3$) δ 8.42 (1H, br), 6.65 (1H, d, J = 5.9 Hz), 6.44 (1H, d, J = 6.2 Hz), 6.31 (1H, d, J = 5.9 Hz), 5.71 (1H, dd, J = 4.0, 6.2 Hz), 5.70 (1H, d, J = 2.2 Hz), 4.54 (1H, dd, J = 4.4, 11.4 Hz), 4.41 (1H, ddd, J = 4.0, 4.4, 6.6 Hz), 4.35 (1H, dd, J = 6.6, 11.4 Hz), 2.13, 2.10 and 2.04 (9H, each as s); FAB MS *m*/*z* 395 (M + H)$^+$. Anal. Calcd for $C_{17}H_{18}N_2O_9 \cdot {}^1/_2H_2O$: C, 50.62; H, 4.75; N, 6.95. Found: C, 50.86; H, 4.55; N, 6.83.

2′,3′,5′-Tri-*O*-acetyl-6,1′-etheno-α-uridine (13α). HPLC purification (75% EtOAc in hexane, retention time of 22.9 min) gave **13**α (8.9 mg, 6.6%) as a solid. Recrystallization from hexane−EtOAc gave an analytical sample: mp 212.0−213.5 °C; $[\alpha]^{23}_D = +442.0$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 290 nm (ϵ 12000), λ_{min} 255 nm (ϵ 3600); ^{1}H NMR ($CDCl_3$) δ 7.91 (1H, br), 6.45 and 6.43 (2H, each as d, J = 6.1 Hz), 5.69 (1H, d, J = 2.2 Hz), 5.53 (1H, d, J = 7.7 Hz), 5.23 (1H, ddd, J = 2.2, 4.4, 7.7 Hz), 5.18 (1H, t, J = 7.7 Hz), 4.44 (1H, dd, J = 2.2, 12.5 Hz), 4.20 (1H, dd, J = 4.4, 12.5 Hz), 2.13, 2.11 and 2.03 (9H, each as s); FAB MS *m*/*z* 395 (M + H)$^+$. Anal. Calcd for $C_{17}H_{18}N_2O_9 \cdot {}^1/_4H_2O$: C, 51.19; H, 4.68; N, 7.02. Found: C, 51.24; H 4.70; N, 6.95.

2′,3′,5′-Tri-*O*-acetyl-6,1′-ethanouridine (18*β*). HPLC purification (80% EtOAc in hexane, retention time of 32.8 min) gave **18***β* (2.5 mg, 1.8%) as an oil: $[\alpha]^{23}_D = -10.4$ (*c* 0.07, $CHCl_3$); UV (MeOH) λ_{max} 259 nm (ϵ 11200), λ_{min} 229 nm (ϵ 2500); ^{1}H NMR ($CDCl_3$) δ 7.89 (1H, br), 6.39 (1H, d, J = 6.2 Hz), 5.69 (1H, dd, J = 4.9, 6.2 Hz), 5.57 (1H, m), 4.45 (1H, dd, J = 3.7, 11.4 Hz), 4.24 (1H, dd, J = 5.8, 11.4 Hz), 4.20 (1H, ddd, J = 3.7, 4.9, 5.8 Hz), 3.02 (1H, dddd, J = 1.8, 8.4, 9.2, 18.0 Hz), 2.81 (1H, dddd, J = 1.1, 2.9, 9.2, 18.0 Hz), 2.43 (1H, dt, J = 9.2, 14.1 Hz), 2.21 (1H, ddd, J = 2.9, 8.4, 14.1 Hz), 2.12, 2.10 and 2.09 (9H, each as s); FAB MS *m*/*z* 397 (M + H)$^+$ and 337 (M − OAc)$^+$. Anal. Calcd for $C_{17}H_{20}N_2O_9$: C, 51.51; H, 5.09; N, 7.07. Found: C, 51.38; H, 4.98; N, 6.90.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*S*)-1-phenylethano]uridine (19*β*). HPLC purification (75% EtOAc in hexane, retention time of 12.8 min) gave **19***β* (12.6 mg, 7.8%) as a solid. Recrystallization from hexane−EtOAc gave an analytical sample: mp 176.5−177.0 °C; $[\alpha]^{23}_D = -144.0$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 259 nm (ϵ 10900), λ_{min} 230 nm (ϵ 2200); ^{1}H NMR ($CDCl_3$) δ 8.09 (1H, br), 7.30∼7.23 (3H, m), 6.99∼6.96 (2H, m), 6.22 (1H, dd, J = 5.3, 8.4 Hz), 6.19 (1H, d, J = 5.3 Hz), 5.63 (1H, br), 4.37 (1H, dd, J = 2.6, 12.1 Hz), 4.26 (1H, ddd, J = 2.6, 5.5, 8.4 Hz), 4.18 (1H, dd, J = 5.5, 12.1 Hz), 3.70 (1H, d, J = 7.1 Hz), 3.55 (1H, ddd, J = 1.8, 7.1, 16.5 Hz), 2.71

(1H, d, J = 16.5 Hz), 2.09, 1.95 and 1.53 (9H, each as s); FAB MS m/z 473 $(M + H)^+$ and 413 $(M - OAc)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9$: C, 58.47; H, 5.12; N, 5.93. Found: C, 58.38; H, 5.19; N, 5.65.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*R*)-1-phenylethano]uridine (20*β*). HPLC purification (75% EtOAc in hexane, retention time of 17.7 min) gave **20***β* (8.4 mg, 5.2%) as a solid. Recrystallization from hexane−EtOAc gave an analytical sample: mp 204.0−205.5 °C; UV (MeOH) λ_{max} 258 nm (ϵ 13000), λ_{min} 231 nm (ϵ 3800); ^{1}H NMR ($CDCl_3$) δ 8.27 (1H, br), 7.50∼7.42 (2H, m), 7.40∼7.32 (3H, m), 6.41 (1H, d, J = 6.6 Hz), 5.64 (1H, t, J = 6.6 Hz), 5.59 (1H, br), 4.36 (1H, dd, J = 4.0, 12.1 Hz), 4.10 (1H, dd, J = 5.9, 12.1 Hz), 3.72 (1H, t, J = 9.5 Hz), 3.50 (1H, ddd, J = 4.0, 5.9, 6.6 Hz), 3.17 (2H, dd, J = 1.1, 9.5 Hz), 2.14, 2.09 and 1.87 (9H, each as s); FAB MS m/z 473 $(M + H)^+$ and 413 $(M - OAc)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9$: C, 58.47; H, 5.12; N, 5.93. Found: C, 58.65; H, 4.97; N, 5.84.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*S*)-1-phenylethano]-α-uridine (19α). HPLC purification (75% EtOAc in hexane, retention time of 20.2 min) gave **19**α (2.3 mg, 1.4%) as an oil: UV (MeOH) λ_{max} 261 nm (ϵ 13000), λ_{min} 230 nm (ϵ 2900); ^{1}H NMR ($CDCl_3$) δ 7.78 (1H, br), 7.51∼7.44 (5H, m), 5.61 (1H, br), 5.28 (1H, d, J = 6.6 Hz), 5.15 (1H, ddd, J = 2.6, 5.5, 9.9 Hz), 4.32 (1H, dd, J = 2.6, 12.5 Hz), 4.16 (1H, dd, J = 5.5, 12.5 Hz), 3.77 (1H, dd, J = 7.0, 13.6 Hz), 3.76 (1H, dd, J = 6.6, 9.9 Hz), 3.50 (1H, ddd, J = 1.8, 13.6, 16.5 Hz), 2.97 (1H, dd, J = 7.0, 16.5 Hz), 2.13, 2.01 and 1.96 (9H, each as s); FAB MS m/z 473 $(M + H)^+$ and 413 $(M - OAc)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9$: C, 58.47; H, 5.12; N, 5.93. Found: C, 58.23; H, 5.24; N, 5.70.

Radical Reaction of (*E*)- and (*Z*)-Haloolefins 7Z, 7E, 8E, and 8Z. 1-[5-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-*β*-D-ribofuranosyl]-6-[(*E*)-ethylidene]-5,6-dihydro-2,4-pyrimidindione (29). This compound was obtained from **7Z** (102.9 mg, 0.204 mmol) by the procedure described for the radical reaction of **1a**. After partial purification by a silica gel column (10−40% EtOAc in hexane), HPLC (50% EtOAc in hexane, 10 mL/min) gave **29** and 6-ethyluridine **30** with the following yields and retention times: **29** (oil, 29.0 mg, 33%, 8.2 min); **30** (oil, 38.9 mg, 45%, 13.0 min). Physical data of **29** are as follows: UV (MeOH) λ_{max} 235 nm (ϵ 4100), λ_{min} 224 nm (ϵ 4000); + 30 min at room temperature; λ_{max} 255 nm (ϵ 5200), λ_{min} 230 nm (ϵ 4000); + 3 h at room temperature; λ_{max} 258 nm (ϵ 9600), λ_{min} 230 nm (ϵ 3500); ^{1}H NMR ($CDCl_3$) δ 7.99 (1H, br), 5.66 (1H, br q, J = 7.0 Hz), 5.54 (1H, d, J = 2.2 Hz), 5.10 (1H, dd, J = 2.2, 6.8 Hz), 4.77 (1H, dd, J = 4.4, 6.8 Hz), 4.08 (1H, ddd, J = 4.4, 4.8, 6.2 Hz), 3.83 (1H, dd, J = 4.8, 11.0 Hz), 3.77 (1H, dd, J = 6.2, 11.0 Hz), 3.39 and 3.23 (2H, each as br d, J = 17.8 Hz), 1.68 (3H, br d), 1.53 and 1.34 (6H, each as s), 0.88 (9H, s), 0.05 and 0.04 (6H, each as s); FAB MS m/z 449 $(M + Na)^+$, 427 $(M + H)^+$, 411 $(M - Me)^+$, and 369 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{34}N_2O_6Si$: C, 56.31; H, 8.03; N, 6.57. Found: C, 56.54; H, 8.22; N, 6.56.

5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-*O*-isopropylidene-6,1′-ethanouridine (14*β*). This compound was obtained from **7E** (154.0 mg, 0.306 mmol), **8E** (140.0 mg, 0.254 mmol), and **8Z** (46.9 mg, 0.0852 mmol) by the procedure described for the radical reaction of **1a**. HPLC (66% EtOAc in hexane) afforded 40.3 mg (31%) of **14***β* (retention time of 13.8 min) as a solid along with 6-ethyluridine **30** (8.4 mg, 6.4%, 14.3 min) in the case of **7E**; 81.8 mg (76%) and 27.9 mg (77%) of **14***β* from the latter two **8E** and **8Z**, respectively. Recrystallization from hexane−EtOAc gave an analytical sample of **14***β*: mp 199.5−200.0 °C; UV (MeOH) λ_{max} 261 nm (ϵ 11000), λ_{min} 230 nm (ϵ 2200); ^{1}H NMR ($CDCl_3$) δ 8.61 (1H, br), 5.57 (1H, br), 5.29 (1H, d, J = 6.2 Hz), 4.93 (1H, dd, J = 4.0, 6.2 Hz), 4.14 (1H, ddd, J = 4.0, 5.3, 7.3 Hz), 3.78 (1H, dd, J = 5.3, 11.0 Hz), 3.73 (1H, dd, J = 7.3, 11.0 Hz), 3.03 (1H, dddd, J = 2.0, 8.1, 11.4, 17.4 Hz), 2.82 (1H, ddd, J = 1.3, 8.4, 17.4 Hz), 2.53 (1H, ddd, J = 8.4, 11.4, 13.9 Hz), 2.24 (1H, ddd, J = 1.3, 8.1, 13.9 Hz), 1.52 and 1.35 (6H, each as s), 0.87 (9H, s), 0.03 (6H, s); FAB MS m/z 425 $(M + H)^+$, 409 $(M - Me)^+$, and 367 $(M - {}^tBu)^+$. Anal. Calcd for $C_{20}H_{32}N_2O_6Si$: C, 56.58; H, 7.60; N, 6.60. Found: C, 56.74; H 7.74; N, 6.65.

Radical Reaction of 2. Compound **2** (161.1 mg, 0.246 mmol) was treated by the procedure described for the radical reaction of **1a**. The following four cyclized products were isolated:

2′-Deoxy-3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-6,1′-ethenouridine (21*β*). After partial purification on a silica gel column (10−33% EtOAc in hexane), preparative TLC (40% EtOAc in hexane) gave **21***β* (27.9 mg, 23%) as a solid, which was recrystallized from hexane−EtOAc for an analytical sample: mp 207.0−207.5 °C; $[\alpha]^{25}_D$ = +3.1 (*c* 1.2, $CHCl_3$); UV (MeOH) λ_{max} 291 nm (ϵ 12500), λ_{min} 252 nm (ϵ 4200); ^{1}H NMR ($CDCl_3$) δ 8.03 (1H, br), 6.59 and 6.35 (2H, each as d, J = 5.9 Hz), 5.63 (1H, d, J = 1.8 Hz), 5.22 (1H, ddd, J = 6.2, 7.5, 8.4 Hz), 4.10 (1H, dd, J = 9.3, 11.9 Hz), 4.01∼3.95 (2H, m), 2.99 (1H, dd, J = 8.4, 13.9 Hz), 2.46 (1H, dd, J = 7.5, 13.9 Hz), 1.15∼1.00 (28H, m, TIPDS); FAB MS m/z 517 $(M + Na)^+$, 495 $(M + H)^+$, and 451 $(M - {}^iPr)^+$. Anal. Calcd for $C_{23}H_{38}N_2O_6Si_2 \cdot {}^1/_4H_2O$: C, 55.33; H, 7.77; N, 5.61. Found: C, 55.35; H, 7.69; N, 5.49.

2′-Deoxy-3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-6,1′-etheno-α-uridine (21α). This compound was obtained (19.2 mg, 16%) by preparative TLC (40% EtOAc in hexane) as a solid, which was recrystallized from hexane−EtOAc for an analytical sample: mp 251.5−252.0 °C; $[\alpha]^{23}_D$ = −27.6 (*c* 0.25, $CHCl_3$); UV (MeOH) λ_{max} 292 nm (ϵ 13000), λ_{min} 254 nm (ϵ 4400); ^{1}H NMR ($CDCl_3$) δ 8.14 (1H, br), 6.42 and 6.33 (2H, each as d, J = 6.0 Hz), 5.65 (1H, d, J = 1.8 Hz), 4.53 (1H, ddd, J = 7.1, 8.8, 10.8 Hz), 4.45 (1H, ddd, J = 2.2, 2.6, 8.8 Hz), 4.00 (1H, dd, J = 2.2, 13.6 Hz), 3.96 (1H, dd, J = 2.6, 13.6 Hz), 3.39 (1H, dd, J = 10.8, 12.5 Hz), 2.33 (1H, dd, J = 7.1, 12.5 Hz), 1.13∼1.00 (28H, m, TIPDS); FAB MS m/z 495 $(M + H)^+$ and 451 $(M - {}^iPr)^+$. Anal. Calcd for $C_{23}H_{38}N_2O_6Si_2 \cdot {}^1/_4H_2O$: C, 55.33; H, 7.77; N, 5.61. Found: C, 55.21; H, 7.74; N, 5.55.

2′-Deoxy-3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-6,1′-ethanouridine (22*β*). This compound was obtained (8.9 mg, 7.3%) by preparative TLC (40% EtOAc in hexane) as a solid, which was analytically pure: mp 185.0−185.5 °C; $[\alpha]^{23}_D$ = +6.5 (*c* 0.6, $CHCl_3$); UV (MeOH) λ_{max} 261 nm (ϵ 11400), λ_{min} 229 nm (ϵ 2000); ^{1}H NMR ($CDCl_3$) δ 7.90 (1H, br), 5.52 (1H, br), 5.07 (1H, ddd, J = 7.0, 8.1, 8.4 Hz), 3.97 (1H, dd, J = 3.7, 12.1 Hz), 3.92 (1H, dd, J = 6.2, 12.1 Hz), 3.71 (1H, ddd, J = 3.7, 6.2, 7.0 Hz), 3.25 (1H, dd, J = 8.1, 13.6 Hz), 3.00 (1H, dddd, J = 1.8, 8.1, 11.4, 17.2 Hz), 2.77 (1H, dd, J = 8.4, 17.2 Hz), 2.37 (1H, dd, J = 8.1, 13.2 Hz), 2.26 (1H, dd, J = 8.4, 13.6 Hz), 2.15 (1H, ddd, J = 8.4, 11.4, 13.2 Hz), 1.16∼0.98 (28H, m, TIPDS); FAB MS m/z 519 $(M + Na)^+$, 497 $(M + H)^+$, and 453 $(M - {}^iPr)^+$. Anal. Calcd for $C_{23}H_{40}N_2O_6Si_2$: C, 55.61; H, 8.12; N, 5.64. Found: C, 55.85; H, 8.04; N, 5.58.

2′-Deoxy-3′,5′-*O*-(tetraisopropyldisiloxan-1,3-diyl)-6,1′-ethano-α-uridine (22α). This compound was obtained (1.6 mg, 1.3%) by preparative TLC (40% EtOAc in hexane) as a solid, which was recrystallized from hexane−EtOAc for an analytical sample: mp 215.0−215.5 °C; $[\alpha]^{25}_D$ = −6.5 (*c* 0.3, $CHCl_3$); UV (MeOH) λ_{max} 263 nm (ϵ 11900), λ_{min} 231 nm (ϵ 2100); ^{1}H NMR ($CDCl_3$) δ 7.81 (1H, br), 5.52 (1H, d, J = 1.1 Hz), 4.47 (1H, ddd, J = 7.3, 8.8, 10.6 Hz), 4.34 (1H, dt, J = 2.2, 8.8 Hz), 3.94 (2H, d, J = 2.2 Hz), 3.35 (1H, dd, J = 10.6, 11.7 Hz), 2.95 (1H, dddd, J = 1.1, 6.6, 8.8, 16.1 Hz), 2.75 (1H, m), 2.35 (1H, ddd, J = 6.6, 9.2, 13.2 Hz), 2.25 (1H, dd, J = 7.3, 11.7 Hz), 2.17 (1H, ddd, J = 6.6, 8.8, 13.2 Hz), 1.11∼0.97 (28H, m, TIPDS); FAB MS m/z 497 $(M + H)^+$ and 453 $(M - {}^iPr)^+$. Anal. Calcd for $C_{23}H_{40}N_2O_6Si_2$: C, 55.61; H, 8.12; N, 5.64. Found: C, 55.36; H, 7.99; N, 5.60.

Radical Reaction of 9. Compound **9** (105.2 mg, 0.161 mmol) was treated by the procedure described for the radical reaction of **1a**. HPLC isolation (33% EtOAc in hexane) gave *β*- and α-6,1′-etheno compounds **21***β* (20.1 mg, 25%) and **21**α (12.5 mg, 16%).

Radical Reaction of 4a. Compound **4a** (52.8 mg, 0.0804 mmol) was treated by the procedure described for the radical reaction of **1a**. The following four cyclized products were isolated after preparative TLC (33% EtOAc in hexane):

3′,5′-Bis-*O*-(*tert*-butyldimethylsilyl)-6,1′-ethenospongouridine (23*β*). This compound (4.5 mg, 11%) was obtained as

an oil: $[\alpha]^{24}_D = -0.5$ (*c* 0.2, $CHCl_3$); UV (MeOH) λ_{max} 293 nm (ϵ 12400), λ_{min} 253 nm (ϵ 3900), $\lambda_{shoulder}$ 303 nm (ϵ 11200); ^{1}H NMR ($CDCl_3$) δ 8.25 (1H, br), 6.66 and 6.39 (2H, each as d, J = 6.0 Hz), 5.70 (1H, d, J = 1.8 Hz), 4.53 (1H, t, J = 5.3 Hz), 4.27 (1H, dd, J = 5.3, 10.6 Hz), 3.91∼3.87 (3H, m), 3.59 (1H, d, J = 10.6 Hz), 0.91 and 0.90 (18H, each as s), 0.15, 0.13, 0.07 and 0.06 (12H, each as s); FAB MS *m*/*z* 519 $(M + Na)^+$, 497 $(M + H)^+$, 481 $(M - Me)^+$, and 439 $(M - {}^tBu)^+$. Anal. Calcd for $C_{23}H_{40}N_2O_6Si_2$: C, 55.61; H, 8.12; N, 5.64. Found: C, 55.60; H, 8.25; N, 5.59.

3′,5′-Bis-*O*-(*tert*-butyldimethylsilyl)-6,1′-etheno-α-spongouridine (23α). This compound (10.5 mg, 26%) was obtained as an oil: $[\alpha]^{24}_D = +161.0$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 293 nm (ϵ 12000), λ_{min} 257 nm (ϵ 4400); ^{1}H NMR ($CDCl_3$) δ 8.19 (1H, br), 6.56 and 6.34 (2H, each as d, J = 6.0 Hz), 5.62 (1H, d, J = 1.8 Hz), 5.31 (1H, dd, J = 5.1, 8.4 Hz), 4.43 (1H, dd, J = 8.4, 8.8 Hz), 4.27 (1H, dt, J = 1.8, 8.8 Hz), 3.82 (1H, dd, J = 1.8, 12.5 Hz), 3.69 (1H, dd, J = 1.8, 12.5 Hz), 2.71 (1H, d, J = 5.1 Hz), 0.91 and 0.90 (18H, each as s), 0.14, 0.13, 0.06 and 0.04 (12H, each as s); FAB MS *m*/*z* 519 $(M + Na)^+$, 497 $(M + H)^+$, 481 $(M - Me)^+$, and 439 $(M - {}^tBu)^+$. Anal. Calcd for $C_{23}H_{40}N_2O_6Si_2 \cdot {}^1/_2H_2O$: C, 54.62; H, 8.17; N, 5.54. Found: C, 54.74; H, 8.03; N, 5.44.

3′,5′-Bis-*O*-(*tert*-butyldimethylsilyl)-6,1′-ethanospongouridine (25*β*). This compound (3.0 mg, 7.5%) was obtained as an oil: $[\alpha]^{24}_D = +34.0$ (*c* 0.2, $CHCl_3$); UV (MeOH) λ_{max} 262 nm (ϵ 11200), λ_{min} 231 nm (ϵ 2100); ^{1}H NMR ($CDCl_3$) δ 8.49 (1H, br), 5.64 (1H, s), 4.60 (1H, t, J = 7.5 Hz), 4.17 (1H, dd, J = 7.5, 12.5 Hz), 3.82 (1H, d, J = 12.5 Hz), 3.80 (1H, dd, J = 2.2, 11.7 Hz), 3.70 (1H, dd, J = 5.9, 11.7 Hz), 3.62 (1H, ddd, J = 2.2, 5.9, 7.5 Hz), 3.04 (1H, m), 2.83 (1H, m), 2.34 (1H, ddd, J = 8.8, 11.4, 13.2 Hz), 2.23 (1H, ddd, J = 1.8, 6.6, 13.2 Hz), 0.91 and 0.87 (18H, each as s), 0.12, 0.02 and 0.01 (12H, each as s); FAB MS *m*/*z* 521 $(M + Na)^+$, 499 $(M + H)^+$, 483 $(M - Me)^+$, and 441 $(M - {}^tBu)^+$. Anal. Calcd for $C_{23}H_{42}N_2O_6Si_2$: C, 55.39; H, 8.49; N, 5.62. Found: C, 55.59; H, 8.60; N, 5.56.

3′,5′-Bis-*O*-(*tert*-butyldimethylsilyl)-6,1′-[(1*R*)-1-phenylethano]spongouridine (26*β*). This compound (5.7 mg, 12%) was obtained as an oil: UV (MeOH) λ_{max} 260 nm (ϵ 13000), λ_{min} 231 nm (ϵ 3300); ^{1}H NMR ($CDCl_3$) δ 8.73 (1H, br), 7.47∼7.45 (2H, m), 7.39∼7.37 (3H, m), 5.69 (1H, br), 4.53 (1H, dd, J = 8.1, 8.8 Hz), 3.99 (1H, dd, J = 8.1, 12.8 Hz), 3.85 (1H, d, J = 12.8 Hz), 3.65 (1H, dd, J = 1.8, 11.7 Hz), 3.55 (1H, dd, J = 5.9, 11.7 Hz), 3.47 (1H, dd, J = 7.7, 12.2 Hz), 3.31 (1H, ddd, J = 1.5, 12.2, 17.4 Hz), 3.13 (1H, dd, J = 7.7, 17.4 Hz), 2.67 (1H, ddd, J = 1.8, 5.9, 8.8 Hz), 0.88 and 0.81 (18H, each as s), 0.10, 0.03 and −0.01 (12H, each as s); FAB MS *m*/*z* 575 $(M + H)^+$, 559 $(M - Me)^+$, and 517 $(M - {}^tBu)^+$. Anal. Calcd for $C_{29}H_{46}N_2O_6Si_2$: C, 60.59; H, 8.07; N, 4.87. Found: C, 60.34; H, 8.07; N, 4.82.

Radical Reaction of 4b. Compound **4b** (102.4 mg, 0.185 mmol) was treated by the procedure described for the radical reaction of **1a**. The following six cyclized products were isolated by HPLC (20% hexane in EtOAc). Compounds **24***β* and **27***β*, which showed the same retention time on HPLC, were isolated by preparative TLC (hexane/EtOAc = 1/1):

2′,3′,5′-Tri-*O*-acetyl-6,1′-ethenospongouridine (24*β*). HPLC (retention time 15.3 min) and following preparative TLC gave **24***β* (8.4 mg, 12%) as an oil: $[\alpha]^{24}_D = -192.3$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 289 nm (ϵ 12200), λ_{min} 253 nm (ϵ 4100); ^{1}H NMR ($CDCl_3$) δ 7.96 (1H, br), 6.55 and 6.43 (2H, each as d, J = 6.0 Hz), 6.10 (1H, dd, J = 7.7, 8.1 Hz), 5.76 (1H, d, J = 7.7 Hz), 5.68 (1H, d, J = 1.8 Hz), 4.56 (1H, dd, J = 2.9, 12.1 Hz), 4.46 (1H, dd, J = 8.1, 12.1 Hz), 4.32 (1H, dt, J = 2.9, 8.1 Hz), 2.09, 2.07 and 2.01 (9H, each as s); FAB MS *m*/*z* 395 $(M + H)^+$. Anal. Calcd for $C_{17}H_{18}N_2O_9$: C, 51.78; H, 4.61; N, 7.10. Found: C, 51.88; H, 4.42; N, 7.03.

2′,3′,5′-Tri-*O*-acetyl-6,1′-etheno-α-spongouridine (24α). This compound (18.7 mg, 26%; retention time of 18.6 min) was obtained as an oil: $[\alpha]^{25}_D = +229.7$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 291 nm (ϵ 11600), λ_{min} 256 nm (ϵ 3600); ^{1}H NMR ($CDCl_3$) δ 8.34 (1H, br), 6.45 and 6.42 (2H, each as d, J = 6.0 Hz), 6.37 (1H, d, J = 7.7 Hz), 5.71 (1H, d, J = 1.8 Hz), 5.54 (1H, dd, J = 7.7, 9.2 Hz), 4.88 (1H, ddd, J = 2.6, 4.8, 9.2 Hz), 4.36 (1H, dd, J = 2.6, 12.5 Hz), 4.13 (1H, dd, J = 4.8, 12.5 Hz), 2.13, 2.11 and 2.03 (9H, each as s); FAB MS *m*/*z* 395 $(M + H)^+$. Anal. Calcd for $C_{17}H_{18}N_2O_9$: C, 51.78; H, 4.61; N, 7.10. Found: C, 51.47; H, 4.58; N, 6.96.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*S*)-1-phenylethano]spongouridine (27*β*). HPLC (retention time 15.3 min) and following preparative TLC gave **27***β* (6.9 mg, 7.9%) as an oil: UV (MeOH) λ_{max} 259 nm (ϵ 12700), λ_{min} 229 nm (ϵ 2700); ^{1}H NMR ($CDCl_3$) δ 8.11 (1H, br), 7.52∼7.35 (5H, m), 5.80 (1H, dd, J = 7.0, 8.1 Hz), 5.63 (1H, br), 5.20 (1H, d, J = 7.0 Hz), 4.46 (2H, m), 4.06 (1H, m), 3.90 (1H, t, J = 9.5 Hz), 3.08 (2H, d, J = 9.5 Hz), 2.11, 1.93 and 1.90 (9H, each as s); FAB MS *m*/*z* 473 $(M + H)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9 \cdot {}^1/_2H_2O$: C, 57.38; H, 5.23; N, 5.82. Found: C, 57.39; H, 5.20; N, 5.58.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*R*)-1-phenylethano]spongouridine (28*β*). This compound (1.8 mg, 2.1%; retention time of 17.0 min) was obtained as an oil: UV (MeOH) λ_{max} 259 nm (ϵ 12700), λ_{min} 230 nm (ϵ 3500); ^{1}H NMR ($CDCl_3$) δ 7.90 (1H, br), 7.52∼7.42 (5H, m), 6.01 (1H, t, J = 7.9 Hz), 5.63 (1H, d, J = 7.9 Hz), 5.61 (1H, br), 4.28 (1H, dd, J = 3.3, 12.1 Hz), 4.11 (1H, dd, J = 6.8, 12.1 Hz), 3.64 (1H, dd, J = 8.2, 12.1 Hz), 3.23 (1H, ddd, J = 1.8, 12.1, 17.2 Hz), 3.13 (1H, ddd, J = 3.3, 6.8, 7.9 Hz), 3.10 (1H, dd, J = 8.2, 17.2 Hz), 2.14, 2.05 and 1.96 (9H, each as s); FAB MS *m*/*z* 473 $(M + H)^+$ and 413 $(M - OAc)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9 \cdot {}^2/_3H_2O$: C, 57.02; H, 5.27; N, 5.78. Found: C, 56.89; H, 4.97; N, 5.62.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*S*)-1-phenylethano]-α-spongouridine (27α). This compound (3.2 mg, 3.7%; retention time of 17.4 min) was obtained as an oil, and physical data are as follows: $[\alpha]^{25}_D = +59.0$ (*c* 0.1, $CHCl_3$); UV (MeOH) λ_{max} 260 nm (ϵ 12100), λ_{min} 230 nm (ϵ 3100); ^{1}H NMR ($CDCl_3$) δ 8.17 (1H, br), 7.41∼7.37 (5H, m), 6.88 (1H, d, J = 7.7 Hz), 5.61 (1H, br), 4.67 (1H, dd, J = 7.7, 9.5 Hz), 4.59 (1H, ddd, J = 2.6, 6.6, 9.5 Hz), 3.85 (1H, dd, J = 2.6, 12.5 Hz), 3.67 (1H, dd, J = 8.4, 11.7 Hz), 3.53 (1H, dd, J = 6.6, 12.5 Hz), 3.25 (1H, ddd, J = 1.8, 11.7, 16.9 Hz), 3.10 (1H, dd, J = 8.4, 16.9 Hz), 2.24, 2.03 and 1.95 (9H, each as s); FAB MS *m*/*z* 473 $(M + H)^+$ and 413 $(M - OAc)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9 \cdot {}^1/_2H_2O$: C, 57.38; H, 5.23; N, 5.82. Found: C, 57.67; H, 5.19; N, 5.60.

2′,3′,5′-Tri-*O*-acetyl-6,1′-[(1*R*)-1-phenylethano]-α-spongouridine (28α). This compound (5.9 mg, 6.5%; retention time of 20.2 min) was obtained as an oil, and physical data are as follows: UV (MeOH) λ_{max} 261 nm (ϵ 13500), λ_{min} 230 nm (ϵ 3200); ^{1}H NMR ($CDCl_3$) δ 8.11 (1H, br), 7.42∼7.34 (5H, m), 6.18 (1H, d, J = 7.3 Hz), 5.65 (1H, br), 4.88∼4.84 (2H, m), 4.31∼4.30 (2H, m), 3.83 (1H, dd, J = 7.9, 10.8 Hz), 3.12 (1H, ddd, J = 1.1, 7.9, 16.1 Hz), 3.06 (1H, ddd, J = 1.5, 10.8, 16.1 Hz), 2.17, 1.99 and 1.79 (9H, each as s); FAB MS *m*/*z* 473 $(M + H)^+$. Anal. Calcd for $C_{23}H_{24}N_2O_9 \cdot {}^1/_2H_2O$: C, 57.38; H, 5.23; N, 5.82. Found: C, 57.18; H, 4.92; N, 5.64.

Radical Reaction of 10. Compound **10** (238.0 mg, 0.293 mmol) was treated by the procedure described for the radical reaction of **1a**. The following three cyclized products were isolated by HPLC:

6-Chloro-8,1′-etheno-2′,3′,5′-tris-*O*-(*tert*-butyldimethylsilyl)nebularine (32*β*). HPLC purification (11% EtOAc in hexane, retention time of 18.3 min) gave **32***β* (34.5 mg, 18%) as an oil: UV (MeOH) λ_{max} 308 nm (ϵ 7900), 295 nm (ϵ 15100), and 286 nm (ϵ 14600), λ_{min} 306 nm (ϵ 7800), 291 nm (ϵ 14000), and 241 nm (ϵ 3700); ^{1}H NMR ($CDCl_3$) δ 8.60 (1H, s), 7.23 and 6.68 (2H, each as d, J = 6.2 Hz), 5.10 (1H, d, J = 4.4 Hz), 4.50 (1H, dd, J = 0.6, 4.4 Hz), 4.25 (1H, ddd, J = 0.6, 5.1, 8.3 Hz), 4.10 (1H, dd, J = 8.3, 11.0 Hz), 3.87 (1H, dd, J = 5.1, 11.0 Hz), 0.96, 0.95 and 0.70 (27H, each as s), 0.16, 0.15, 0.13, 0.12, −0.14 and −0.60 (18H, each as s); FAB MS *m*/*z* 655 and 653 $(M + H)^+$, 597 and 595 $(M - {}^tBu)^+$. Anal. Calcd for $C_{30}H_{53}ClN_4O_4Si_3$: C, 55.14; H, 8.18; N, 8.57. Found: C, 55.36; H, 8.58; N, 8.55.

6-Chloro-8,1′-etheno-2′,3′,5′-tris-*O*-(*tert*-butyldimethylsilyl)-α-nebularine (32α). HPLC purification (17% EtOAc in hexane, retention time of 11.2 min) gave **32**α (26.8 mg, 14%) as an oil: UV (MeOH) λ_{max} 310 nm (ϵ 7900), 297 nm (ϵ 15100), and 288 nm (ϵ 14600), λ_{min} 307 nm (ϵ 7800), 293 nm (ϵ 14000), and 246 (ϵ 3700); ^{1}H NMR ($CDCl_3$) δ 8.61 (1H, s), 6.78 and

6.76 (2H, each as d, $J = 6.0$ Hz), 4.78 (1H, dt, $J = 2.0$, 4.8 Hz), 4.46 (1H, d, $J = 6.2$ Hz), 4.42 (1H, dd, $J = 4.8$, 6.2 Hz), 3.92 and 3.82 (2H, each as dd, $J = 2.0$, 11.8 Hz), 0.97, 0.93 and 0.53 (27H, each as s), 0.18, 0.11, 0.09, 0.08, −0.04 and −0.39 (18H, each as s); FAB MS *m*/*z* 655 and 653 $(M + H)^+$, 597 and 595 $(M - {}^t\mathrm{Bu})^+$. Anal. Calcd for $C_{30}H_{53}ClN_4O_4Si_3$: C, 55.14; H, 8.18; N, 8.57. Found: C, 55.33; H, 8.24; N, 8.55.

6-Chloro-8,2′-etheno-2′,3′,5′-tris-*O*-(*tert*-butyldimethylsilyl)nebularine (33). HPLC purification (14% EtOAc in hexane, retention time of 15.1 min) gave **33** (9.6 mg, 5%) as an oil: UV (MeOH) $\lambda_{shoulder}$ 312 nm (ϵ 12000) and 288 nm (ϵ 16800), λ_{max} 300 nm (ϵ 18600), λ_{min} 249 nm (ϵ 3700); ^{1}H NMR ($CDCl_3$) δ 8.76 (1H, s), 6.78 and 6.68 (2H, each as d, $J = 10.6$ Hz), 6.07 (1H, s), 4.17 (1H, d, $J = 8.4$ Hz), 4.07 (1H, dt, $J = 2.0$, 8.4 Hz), 3.95 and 3.63 (2H, each as dd, $J = 2.0$, 12.3 Hz), 0.93, 0.92 and 0.48 (27H, each as s), 0.14, 0.09, 0.06, 0.00, −0.12 and −0.34 (18H, each as s); FAB MS *m*/*z* 655 and 653 $(M + H)^+$, 597 and 595 $(M - {}^t\mathrm{Bu})^+$. Anal. Calcd for $C_{30}H_{53}ClN_4O_4Si_3$: C, 55.14; H, 8.18; N, 8.57. Found: C, 55.32; H, 8.47; N, 8.27.

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Supporting Information Available: Time course of UV spectra of **29** in MeOH (0, 30, and 180 min) and X-ray structural information on **19**β. This material is available free of charge via the Internet at http://pubs.acs.org.

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