Synthesis of 2-(1-Phosphorylalkyl)- and 2-(1-Alkenyl)furans through Nitrile Oxide Cycloaddition Route

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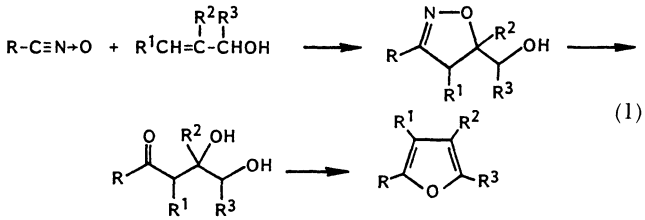
A new synthetic method of 2-(1-phosphorylalkyl)furans with a variety of substituents on the ring is presented. Cycloaddition of (diethoxyphosphoryl)acetonitrile oxide to *O*-protected allyl alcohols is followed by a simple sequential procedure including Raney Ni reduction and acid treatment to give 2-(1-phosphorylmethyl)-furans. The phosphorus-stabilized carbanions derived from the phosphorus-functionalized furans are applied to alkylation, oxidation with oxygen, or olefination to provide 2-(1-phosphorylalkyl)furans, 2-acylfurans, or 2-(1-alkenyl)furans, respectively. Some other synthetic applications are also described.

We have already reported some synthetic applications of a phosphorus-functionalized nitrile oxide, (diethoxyphosphoryl)acetonitrile oxide.[1] It undergoes regioselective 1,3-dipolar cycloadditions to olefins or acetylenes to furnish good yields of 2-isoxazolines[1a,b] or isoxazoles[1c] bearing a phosphorylmethyl moiety at the 3-position. Reductive N-O bond cleavage provides 4-hydroxy-2-oxo- or 2,4-dioxoalkylphosphonates which can be further converted into 1,4-alkadien-3-ones,[1b] 1-hydroxy-4-alken-3-ones,[1d] and 5-(1-alkenyl)-3(2*H*)-furanones.[1c]

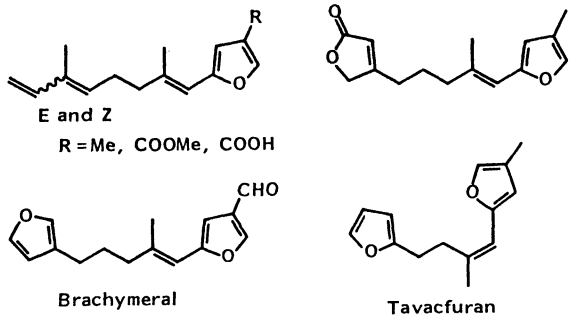
Regioselective cycloadditions of nitrile oxides to allyl alcohols will produce 2-isoxazoline-5-methanols. They are then hydrogenated leading to β,γ-dihydroxy ketones whose acid-catalyzed cyclization would give rise to furans (Eq. 1). Although the last cyclization step has not been well documented before,[2] similar acid-catalyzed furan syntheses from β,γ-epoxy ketones are known.[3] Substitution patterns of the furans depend upon those of the 2-isoxazolines, hence the nitrile oxides and allyl alcohols.



(1)

4-Substituted 2-(1-alkenyl)furan structures often occur in the important family of furanosesquiterpenoids, some of which are illustrated below.[4-8] As a phosphorylmethyl moiety may be introduced at the 2-position of furan rings by the cycloaddition route shown in Eq. 1 using a phosphorylacetonitrile oxide (RCNO, R=$(EtO)_2POCH_2$), this route will find useful synthetic applications in the construction of 2-(1-alkenyl) substituent of these furanosesquiterpenoids, especially the olefin substituent bearing *E*-configuration.

The present article describes a new synthesis of 2-(1-phosphorylmethyl)furans through cycloadditions of a phosphorus-functionalized nitrile oxide to *O*-protected allyl alcohols and a subsequent sequence of reductive N-O bond fission and acid treatment. These furans are further converted into 2-(1-phosphorylalkyl)furans, 2-(1-alkenyl)furans, 2-acylfurans, and 2,5-dioxoalkylphosphonates.



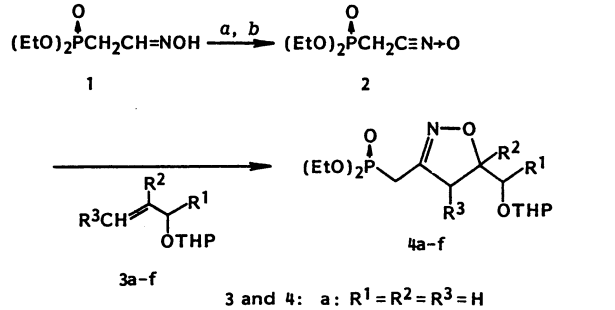
Results and Discussion

Cycloadditions of a Phosphorylacetonitrile Oxide to *O*-Protected Allyl Alcohols Leading to 2-Isoxazolines. The cycloaddition of (diethoxyphosphoryl)acetonitrile oxide (**2**) to allyl alcohol itself was first tried under the reaction conditions previously employed in the successful cycloadditions to olefins.[1a,b] Thus oxime **1** and 2-propen-1-ol (5 equiv) were treated with *N*-bromosuccinimide (NBS, 2 equiv) and triethylamine (1 equiv) in *N*,*N*-dimethylformamide (DMF)-diethyl ether (1 : 1 v/v) at room temperature for 18 h to give only 6% yield of the expected cycloadduct, 3-(diethoxyphosphoryl)methyl-2-isoxazoline-5-methanol, indicating the need of *O*-protection.

Therefore the tetrahydropyranyl (THP, **3a**) and trimethylsilyl ethers of 2-propen-1-ol were employed in the reaction with **2**. Under the same reaction conditions (5 equiv of the ether, rt, 18 h), the THP ether **3a** gave a better yield of cycloadduct **4a** (62%) than the trimethylsilyl ether (32%). When the former reaction was carried out under reflux in a mixed solvent, DMF-diethyl ether-hexane (1 : 1 : 1 v/v), the yield of **4a** was not improved (58%).[9]

Cycloadditions of **2** to a variety of allyl THP ethers

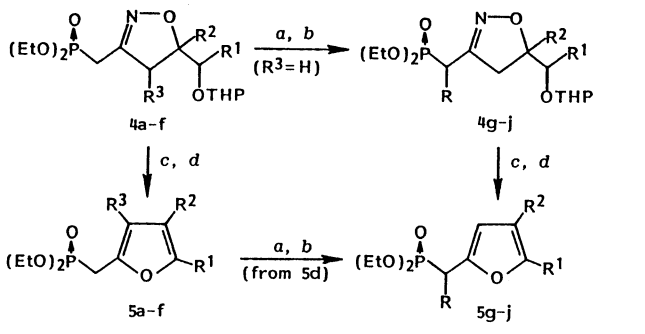
3a—f were performed at room temperature for 18 h by using excess amounts of the ethers **3** (5 equiv). Nitrile oxide **2** was generated in advance from *N*-[2-(diethoxyphosphoryl)ethylidene]hydroxylamine (**1**) according to the reported method (NBS in DMF, −20 °C, 1 h then 0 °C, 0.5 h, NEt_3 in diethyl ether).[1b]



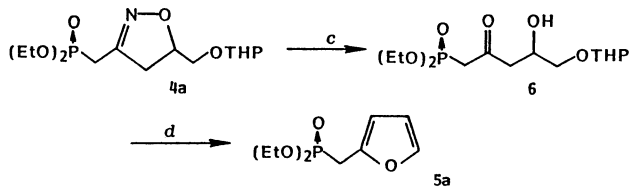
3 and 4: a: $R^1=R^2=R^3=H$
b: $R^1=Me$, $R^2=R^3=H$
c: $R^1=Et$, $R^2=R^3=H$
d: $R^1=R^2=H$, $R^3=Me$
e: $R^1=R^2=H$, $R^3=CH_2OTHP$
f: $R^1=H$, $R^2R^3=(CH_2)_3$

a: NBS (2 equiv) in DMF, -20 °C (1 h) → 0 °C (0.5 h).
b: NEt_3 (1 equiv)

Scheme 1.



4 and 5: a: $R^1=R^2=R^3=H$
b: $R^1=Me$, $R^2=R^3=H$
c: $R^1=Et$, $R^2=R^3=H$
d: $R^1=R^3=H$, $R^2=Me$
e: $R^1=R^2=H$, $R^3=CH_2OTHP$ (5e: $R^3=CH_2OH$)
f: $R^1=H$, $R^2R^3=(CH_2)_3$
g: $R^1=Et$, $R^2=H$, $R=n\text{-}C_8H_{17}$
h: $R^1=Et$, $R^2=H$, $R=n\text{-}C_5H_{11}$
i: $R^1=H$, $R^2=Me$, $R=n\text{-}C_5H_{11}$
j: $R^1=H$, $R^2=Me$, $R=PhCH_2$



a: n-BuLi in THF, -78 °C. *b*: RX, rt. *c*: Raney Ni, $B(OH)_3$, in aq AcOH. *d*: AcONa in AcOH, 100 °C

Scheme 2.

Unsymmetrically mono- and disubstituted olefins provided satisfactory yields of regioselective cycloadducts **4a—d** (62—76% based on the oxime **1**), while a symmetrically disubstituted olefin and a trisubstituted olefin gave **4e** and **4f** only in fair yields (**4e**: 46%. **4f**: 29%. Scheme 1 and Table 1). These cycloadducts **4** were obtained all as mixtures of more than two diastereomers (^1H and ^{13}C NMR), however their separation was not attempted.

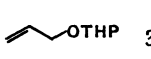
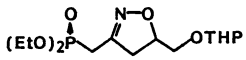
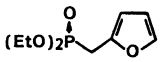
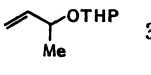
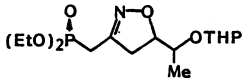
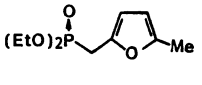
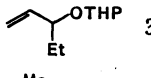
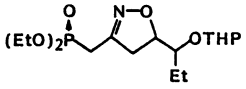
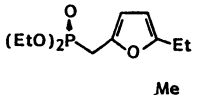
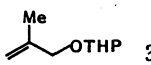
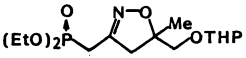
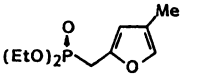
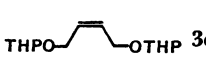
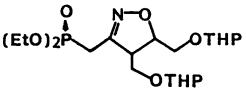
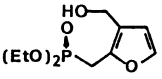
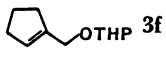
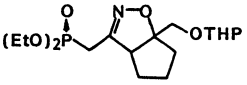
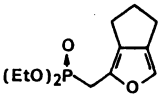
Conversion of 3-(1-Phosphorylalkyl)-2-isoxazolines into 2-(1-Phosphorylalkyl)furans. Conversion of the above cycloadducts, 3-(phosphorylmethyl)-2-isoxazolines **4**, into furans **5** was initially examined by using **4a** as an example (Scheme 2): Hydrogenation of **4a** on Raney Ni (W-2) in aq EtOH in the presence of $B(OH)_3$ gave β-hydroxy ketone **6** with the THP protecting group intact in 87% yield. Heating **6** with AcONa in AcOH at 100—110 °C for 3 h furnished the desired product, 2-[(diethoxyphosphoryl)methyl]furan (**5a**) in 77% yield. Since about a half of **6** is consumed by decomposition in a single operation on silica-gel chromatography, the purification step of **6** was omitted.

Thus the crude reaction mixtures separated in the Raney Ni reduction of isoxazolines **4a—f** were immediately treated with AcONa in AcOH at 90—100 °C for 0.5 h to give the expected furans **5a—f** in satisfactory yields (Scheme 2 and Table 1). As the isoxazoline **4e** affords a mixture of **5e**, its THP ether, and its *O*-acetate when cyclized in acetic acid, the cyclization was carried out in aq tetrahydrofuran (THF) in the presence of *p*-toluenesulfonic acid to give **5e** as a sole product. Yields of **5e** and **5f** are lower than the other cases.

An alkyl group can be introduced at the side chain of 2-isoxazolines **4c** and **4d** via the phosphorus-stabilized carbanions generated by the action of butyllithium to produce 3-(1-phosphorylalkyl)-2-isoxazolines **4g—j** in 59—65% yields. These alkylated 2-isoxazolines **4g—j** can be also converted into the corresponding furans **5g—j** through a sequence of reductive ring opening and acid-catalyzed cyclization (Scheme 2 and Table 2). The furans **5i** and **5j** bearing a methyl substituent at the 4-position were obtained only in fair yields. An alternative and more effective route leading to the furans **5i** and **5j** consists of alkylation after construction of the furan rings as shown in two examples of alkylation of **5d** (87—88%, Scheme 2 and Table 2).

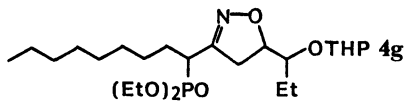
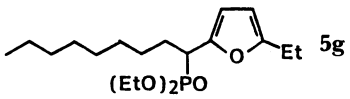
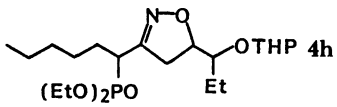
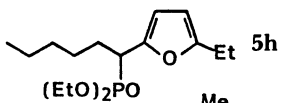
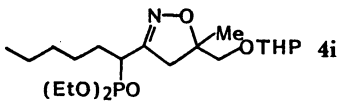
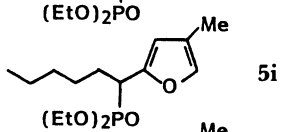
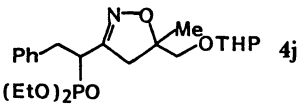
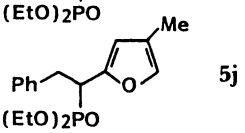
Horner-Emmons Olefinations of 2-(1-Phosphorylalkyl)furans Leading to 2-(1-Alkenyl)furans. Two 2-[(diethoxyphosphoryl)methyl]furans **5b** and **5d** were employed in the Horner-Emmons olefinations using aldehydes: 4-Methylfuran **5d** was deprotonated with butyllithium in THF at −78 °C and then treated with benzaldehyde at room temperature to furnish 61% of (*E*)-4-methyl-2-(2-phenylethenyl)furan (**8b**). On the other hand, only 33% of (*E*)-5-methyl-2-(1-pentenyl)-furan (**8a**) and recovered **5b** (26%) were obtained from 5-methylfuran **5b** and butanal (2 equiv). In this case

Table 1. Cycloaddition of **2** to Allyl Ethers **3** and Subsequent Furan Synthesis

Cycloaddition to allyl ethers 3[a]			Furan synthesis[b,c]			
	**3a**	A[d]		**4a** B (62%)		**5a** (60%)
	**3b**	A		**4b** B (76%)		**5b** (54%)
	**3c**	A		**4c** B (73%)		**5c** (60%)
	**3d**	A		**4d** B (67%)		**5d** (61%)
	**3e**	A		**4e** C (46%)		**5e** (41%)
	**3f**	A		**4f** D (29%)		**5f** (25%)

a) Excess of **3** was used (5 equiv). b) Raney Ni, $B(OH)_3$ in aq EtOH, rt. c) Cyclization to furans **5** was performed under either of the following conditions: B: AcONa in AcOH, 100 °C, 0.5 h. C: *p*-TsOH in aq THF, 70 °C, 8 h. D: AcONa in AcOH, 90 °C, 0.5 h. d) A: rt, 18 h.

Table 2. Synthesis of 2-(1-Phosphorylalkyl)furans **5**

Alkylation of 2-isoxazolines 4[a]		Synthesis of 2-(1-phosphorylalkyl)furans 5[b,c]		
4c	n-$C_8H_{17}I$, 14 h, 64%[d]	 **4g**	64%	 **5g**
4c	n-$C_5H_{11}I$, 14 h, 65%[e]	 **4h**	64%	 **5h**
4d	n-$C_5H_{11}I$, 16 h, 59%[f]	 **4i**	26%	 **5i**
4d	$PhCH_2Br$, 16 h, 65%[g]	 **4j**	16%	 **5j**

Alkylation of furan **5d**[h]

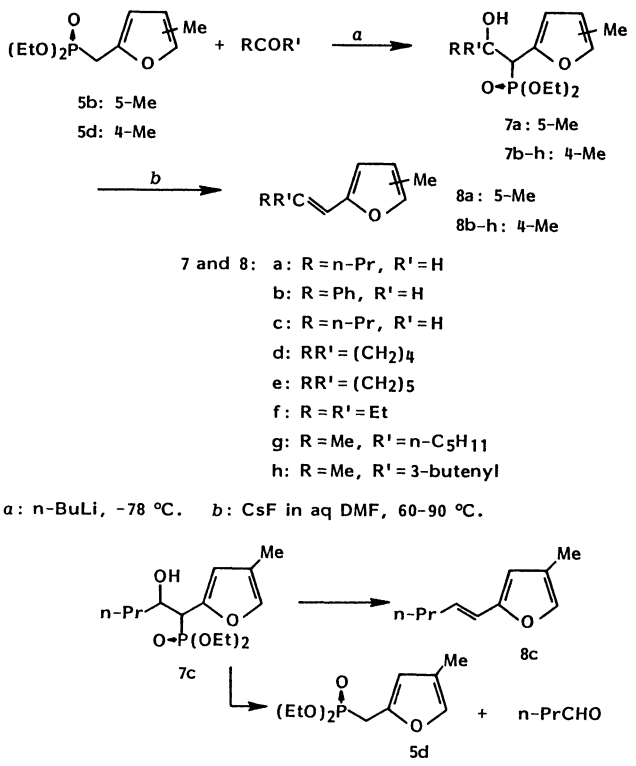
5d —(n-$C_5H_{11}I$, 5 h, 88%)→ **5i**

5d —($PhCH_2Br$, 2.5 h, 87%)→ **5j**

a) Lithiation: *n*-BuLi, −78 °C, 1 h. Alkylation: −78 °C (1 h)→0 °C (1 h)→rt. b) Raney Ni, $B(OH)_3$ in aq EtOH, rt. c) AcONa in AcOH, 100 °C, 0.5 h. d) Recovered **4c**: 8%. e) −78 °C, 1 h. Alkylation: −78 °C.

condensation of butanal itself was the major reaction. Use of sodium hydride instead of butyllithium did not improve the yield of **8a** (29%).

It is known that, in olefination reactions between carbanions derived from alkylphosphonates and aldehydes, the addition step of aldehydes occurs rapidly in high yields but the rate-determining elimination step competes with the retro addition step, resulting in low yield formation of olefins.[10] Recently an example of the effective elimination of a phosphorus moiety from



Scheme 3.

carbonyl adducts has been reported.[11]

The reaction of the carbanion derived from 4-methylfuran **5d** and butyllithium with butanal at −78 °C for 30 min afforded an adduct **7c** as a mixture of two diastereomers (7:3) in 93% yield. The adduct **7c** was then subjected to an olefination by treatment with cesium fluoride and water (each 3.8 equiv) in DMF at 60 °C for 36 h to give 4-methyl-2-(1-pentenyl)furan (**8c**) (*E*:*Z*=96:4) in 64% yield together with the recovered **7c** (18%) and 4-methyl-2-(phosphorylmethyl)furan (**5d**) (4%) (Scheme 3). The latter compound **5d** corresponds to a retro-addition product of **7c**.

This two-step olefination procedure of 4-methyl-2-(phosphorylmethyl)furan **5d** was applied to some other carbonyl compounds. Like aldehydes, cyclic and acyclic ketones undergo smooth additions to furnish adducts **7d—h** whose elimination reactions are even cleaner than those of the aldehyde adducts **7b** and **7c** to produce 2-(1-alkenyl)-4-methylfurans **8d—h** (Scheme 3 and Table 3). Total yields of **8** are 49—71% based on **5** except for **8a** which was obtained by the one-pot procedure without isolation of **7a**. Compared to the almost exclusive formation of (*E*)-olefins (**8b** and **8c**) from the aldehyde adducts **7b** and **7c**, *E*-selectivities are only higher than 80% in olefinations from the adducts (**7g** and **7h**) to unsymmetrical ketones.

Table 3. Olefination of 2-(Phosphorylmethyl)furans **5**

Addition of **5** to aldehydes or ketones[a]		Synthesis of 2-(1-alkenyl)furans **8**[b]									
			Yield/%[c]					Yield/%[c]			*E*:*Z*[d]
5b+butanal	A	**7a**[e]					**8a**	33[f]	26*	—	98:2
5d+benzaldehyde	B	**7b**	93	7:3[g]	C		**8b**	53	—	20**	99:1
5d+butanal	B	**7c**	89	4:1[g]	C		**8c**	64	18*	4**	96:4
5d+cyclopentanone	B	**7d**	91	4*	C	51 h	**8d**	78	3*	6**	—
5d+cyclohexanone	B	**7e**	80	6*	C	33 h	**8e**	85	5*	—	—
5d+3-pentanone	B	**7f**	80	9*	C	30 h	**8f**	75	3*	8**	—
5d+2-heptanone	B	**7g**	88	3*	4:1[g]	C 30 h	**8g**	73	6*	10**	80:20
5d+5-hexen-2-one	B	**7h**	90	2*	4:1[g]	C 30 h	**8h**	67	4*	12**	82:18

a) A: NaH (1.2 equiv), rt, 2h; butanal (2 equiv), rt, 2h. B: *n*-BuLi, −78 °C, 1 h; a carbonyl compound (1.5 equiv), −78 °C, 0.5 h. b) C: CsF (3.8 equiv) in aq DMF, 60 °C. c) Yield of isolated products. Yield with an asterisk: recovered **5** or **7**; two asterisks: retro aldol product **5**. d) Determined by GLC. e) Not isolated. f) Yield based on **5b**. g) Diastereomer ratio (^{1}H NMR).

Though the adduct **7b** was a 7:3 mixture of two diastereomers, *E*-selectivity in the olefination leading to **8b** is as high as 99% (Table 3). Under our elimination conditions (CsF in aqueous DMF at 60 °C), it is unlikely to happen that the anion of adduct **7b** is equilibrating with benzaldehyde and the anion of **5d**, a retro addition. Accordingly the high *E*-selectivity must be a kinetical result: Based on steric hindrance in the transition states, the major isomer **B** whose cis elimination leads to the *E*-isomer (*E*)-**8b** should undergo much more ready elimination than the other diastereomer **C** (Fig. 1, R=Ph). As a result, the retro addition product **5d** (20%) presumably arises mainly from the unreacted diastereomer **C** (R=Ph).

Similar kinetical resolution is observed in the olefination of **7c** (4:1) producing **8c** (64%, *E*:*Z*=96:4). In this case the unreacted **7c** recovered in 18% yield consists of almost pure diastereomer **C** (R=*n*-Pr), indicating the rapid olefin formation from the major diastereomer **B** (R=*n*-Pr).

Predominant formation of the diastereomers **B** over the other **C** in the addition reactions of lithiated **5d** with aldehydes can be well-interpreted with a six-membered chelation model (Fig. 1). The chair transition state **A** with two bulky substituents (4-methyl-2-furyl and R) at equatorial positions gives the major diastereomers **B**.

Two diastereomers of the adduct **7g** or **7h** to unsymmetrical ketones do not show such different reactivity in the elimination leading to **8g** or **8h**. Thus the isomer ratios between the two diastereomers of **7g** or **7h** (both 4:1) are nearly equal to those between the *E*- and *Z*-isomers of **8g** (80:20) or **8h** (82:18) (Table 3).

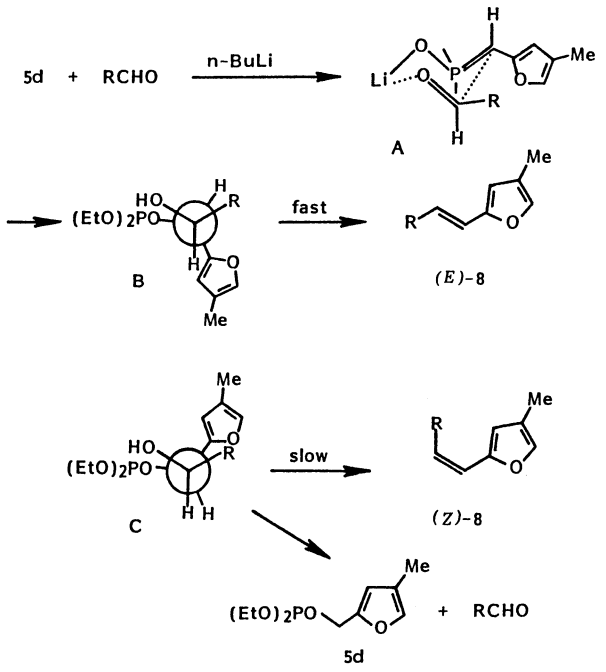
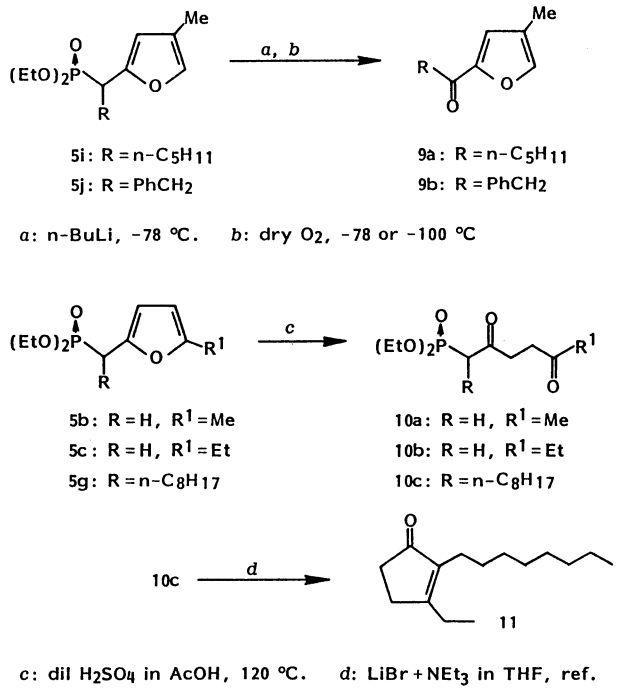


Fig. 1. Stereochemistry of Horner-Emmons olefinations of **5d** with aldehydes.

Conversion of 2-(1-Phosphorylalkyl)furans into 2-Acylfurans and 2,5-Dioxoalkylphosphonates. Air-oxidation of phosphorus-stabilized carbanions offers a simple preparation of ketones.[12] According to our previous procedure[1a,b] by which 3-acyl-2-isoxazolines have been prepared from 3-(1-phosphorylalkyl)-2-isoxazolines, the carbanion generated from 4-methyl-2-(1-phosphorylalkyl)furans **5i** and butyllithium was oxidized by dry oxygen at −78 °C to give 2-acylfuran **9a** in 30% yield (Scheme 4). Monitoring this reaction by thin-layer chromatography (TLC) showed the formation of complex mixture. Presumably the ketone **9a** as a product further reacted with the starting carbanion. So the carbanion of **5j** was oxidized at −100 °C in order to avoid the further condensation, but again only a low yield (20%) of **9b** was afforded.

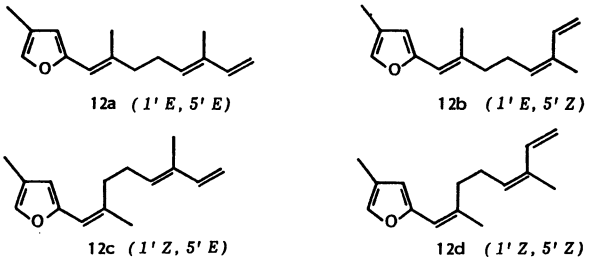
On the other hand 5-substituted 2-(1-phosphorylalkyl)-furans **5** can be converted into 2,5-dioxoalkylphosphonates **10** through the usual hydrolysis method of furan rings.[13] Thus **5b**, **5c**, and **5g** were heated at 120 °C together with a catalytic amount of sulfuric acid in aqueous acetic acid to furnish moderate yields of 1,4-diketones **10a—c**, respectively, with the phosphoryl moiety intact (Scheme 4).

Though intramolecular cyclization of 1,4-diketones is one of the most important accesses to cyclopentenones, its regiochemical control has been a serious problem.[14] As the use of 2,5-dioxoalkylphosphonates will enable regioselective cyclization,[15] **10c** was treated with triethylamine (1.1 equiv) in the presence of lithium bromide (1.5 equiv) in refluxing THF to give 31% of 3-ethyl-2-octyl-2-cyclopenten-1-one (**11**) (Scheme 4).

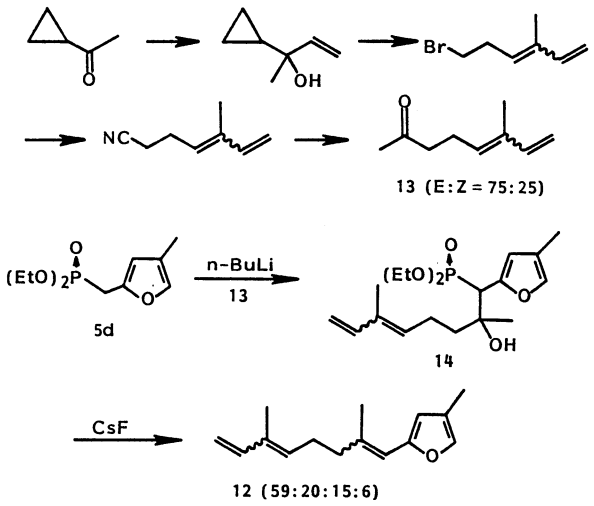


Scheme 4.

Table 4. ^{13}C NMR Chemical Shifts of **12a—d**



	2'-Me	3'-C	5'-C	6'-C	6'-Me	7'-C	8'-C
12a	18.52	40.36	132.13	134.38	11.68	141.49	110.64
12b	19.74	40.75	130.15	133.63	19.74	133.63	113.57
12c	24.71	33.38	132.65	134.31	11.63	141.56	110.89
12d	25.74	33.78	130.58	133.74	19.74	133.74	113.42



Scheme 5.

Synthesis of a Furanosesquiterpene. As briefly shown in the introduction, there are several furanosesquiterpenoids which bear a general structure of (*E*)-4-methyl-2-(2-methyl-1-alkenyl)furans. They would be readily accessible by the Horner-Emmons olefination of 4-methyl-2-[(diethoxyphosphoryl)methyl]furan (**5d**) with methyl ketones. Furanosesquiterpene **12**,[4] isolated from an Australian soft coral, also belongs to this family. And two isomers, (1'*E*, 5'*E*)-isomer **12a** and (1'*E*, 5'*Z*)-isomer **12b**, of 4-methyl-2-(2,6-dimethyl-1,5,7-octatrienyl)furan are naturally occurring. *E*-Geometry at the 1-position of the alkatrienyl substituent of **12** will be conveniently constructed by use of the Horner-Emmons olefination of **5d**.

6-Methyl-5,7-octadien-2-one (**13**) is the requisite ketone, and a mixture of *E*- and *Z*-isomers of **13** has been previously prepared.[16,17] A 75:25 inseparable mixture (GLC in a capillary column) of *E*- and *Z*-isomers of **13** was prepared according to this method (Scheme 5).

After 4-methyl-2-(phosphorylmethyl)furan **5d** was lithiated with butyllithium in THF, the resulting anion was allowed to react with the ketone **13** (1.5 equiv) at −78 °C for 30 min to give 79% of the adduct **14**. Though *E*:*Z* ratio of **14** was found to be 3:1 (by ^1H NMR), its diastereomer ratio could not be determined. The crude **14** was therefore treated with cesium fluoride (3.8 equiv) in aq DMF at 60 °C for 38 h to produce a mixture of four isomers of the desired furanosesquiterpene **12** in 60% yield.

The product **12** contains four isomers in a 59:20:15:6 isomer ratio (GLC in a capillary column). The two major products were identified to be (1'*E*, 5'*E*)-**12a** and (1'*E*, 5'*Z*)-isomer **12b** by comparison of the ^1H and ^{13}C NMR spectra with those of natural products.[4] The ratio **12a**/**12b** (59/20) is almost equal to the *E*/*Z* ratio (3/1) of the starting ketone **13**, confirming the 1'*E*, 5'*E* and 1'*E*, 5'*Z* structures of **12a** and **12b**. The remaining two minor products should have 1'*Z* geometry, and were determined to be (1'*Z*, 5'*E*)- **12c** and (1'*Z*, 5'*Z*)-isomer **12d** on the basis of the isomer ratio (15/6) as well as the NMR data, especially the ^{13}C NMR chemical shifts of 2'-Me, 3'-C, 5'-C, 6'-Me, and 8'-C (Table 4). *E*-Selectivity of the Horner-Emmons olefination is estimated to be 79:21 which is comparable to the selectivities obtained in similar olefinations using other methyl ketones (Table 3).

Separation of each isomer from the mixture was attempted by column chromatography on silica gel, thin-layer chromatography on silica gel containing 2% of silver nitrate, or high performance liquid chromatography (HPLC), but not even one of them could be isolated. Though gas-liquid chromatography (GLC) in a capillary column separates the four isomers, no separation was made on a preparative scale by GLC.

Experimental

General. Melting points were determined on a Yanagimoto melting point apparatus and are uncorrected. IR spectra were taken with a JASCO IRA-1 or a JASCO A-702 spectrometer. ^1H NMR spectra were recorded on a Hitachi R-40 (90 MHz), a JEOL FX-100 (100 MHz), or a JEOL GSX-270

(270 MHz) instrument and ^{13}C NMR on a JEOL FX-100 (25.05 MHz) or a GSX-270 spectrometer (67.94 MHz). Chemical shifts are expressed in parts per million downfield from tetramethylsilane as an internal standard. Mass spectra were measured with a JEOL-OlSG-2 spectrometer at 70 eV of ionization energy. High-resolution mass spectra were obtained on the same instrument. Elemental analyses were performed on a Hitachi 026 CHN analyzer. Thin-layer chromatography (TLC) was accomplished on 0.2 mm precoated plates of silica gel 60 F-254 (Merck). Visualization was made with ultraviolet light (254 and 365 nm), iodine, molybdophosphoric acid (5% in ethanol), or *p*-anisaldehyde (5% in ethanol containing 5% of sulfuric acid). For preparative column chromatography, Wakogel C-200, C-300 (Wako), and Silicagel 60 (Merck) were employed. preparative high-performance liquid chromatography (HPLC) was performed on a Kusano KHLC-201 apparatus with a UV-detector Uvilog-III using a column (22×300 mm) packed with silica gel (Wakogel LC-50H). Gas liquid chromatography (GLC) was accomplished on a Yanaco G-2800 gas chromatograph (Yanagimoto) with an ionization flame detector using a glass column (SE-30, 3×2000 mm) or a glass capillary column (Silicone GE, SE-30, 0.25×50000 mm). Micro vacuum distillation was carried out on a Sibata GTO-250R Kugelrohr distilling apparatus. Solvents were evaporated with a Tokyo Rikakikai rotary evaporator type-V at about 50 °C unless otherwise stated.

Materials. Tetrahydrofuran (THF) was distilled over lithium aluminum hydride in prior to its use. 2-(Diethoxyphosphoryl)acetaldehyde oxime (**1**) was prepared by the reaction with hydroxylamine hydrochloride according to the reported method.[1b] Allyl tetrahydropyranyl ethers **3a—f** were synthesized from the corresponding allyl alcohols and 3,4-dihydro-2*H*-pyran.[18] The boiling points and ^1H NMR spectra are given as follows: **3a**: Bp 80—83 °C/5187 Pa; ^1H NMR ($CDCl_3$) δ=1.4—2.0 (6H, m, THP), 3.3—4.4 (4H, m, CH_2OTHP and THP), 4.56 (1H, m, THP), 5.0—5.4 (2H, m, $=CH_2$), and 5.7—6.1 (1H, m, =CH). **3b**: Bp 87—90 °C/4522 Pa; ^1H NMR ($CDCl_3$) δ=1.4—2.0 (6H, m, THP), 1.72 (3H, s, Me), 3.3—4.3 (4H, m, CH_2OTHP and THP), 4.53 (1H, m, THP), and 4.7—5.0 (2H, m, $=CH_2$). **3c** (a mixture of two diastereomers): Bp 83—85 °C/4655 Pa; ^1H NMR ($CDCl_3$) δ=1.19, 1.27 (3H, each d, J=7.0 Hz, Me), 1.4—2.1 (6H, m, THP), 3.3—4.0 (2H, m, THP), 4.15, 4.23 (1H, each dq, CHOTHP), 4.60 (1H, m, THP), 4.9—5.3 (2H, m, $=CH_2$), and 5.4—6.1 (1H, m, =CH). **3d** (a mixture of two diastereomers): Bp 97—100 °C/4655 Pa; ^1H NMR ($CDCl_3$) δ=0.87, 0.93 (3H, each t, J=7.0 Hz, Et), 1.3—2.0 (8H, m, Et and THP), 3.3—4.1 (3H, m, CHOTHP and THP), 4.60 (1H, m, THP), 4.9—5.3 (2H, m, $=CH_2$), and 5.4—6.0 (1H, m, =CH). **3e**: Bp 125—127 °C/200 Pa; ^1H NMR ($CDCl_3$) δ=1.4—2.2 (12H, m, THP), 3.3—4.4 (8H, m, CH_2OTHP and THP), 4.55 (2H, m, THP), and 5.66 (2H, m, =CH). **3f**: Bp 150—155 °C/3325 Pa (bulb-to-bulb); ^1H NMR ($CDCl_3$) δ=1.1—2.1 (8H, m, THP and cyclopentenyl), 2.31 (4H, t, J=7.0 Hz, cyclopentenyl), 3.3—4.4 (4H, m, CH_2OTHP and THP), 4.59 (1H, m, THP), and 5.61 (1H, m, =CH). 6-Methyl-5,7-octadien-2-one (**13**) was prepared as a 75:25 mixture of *E*- and *Z*-isomers (GLC) from the commercially available 3-acetyltetrahydrofuran-2-one according to the known methods.[16,17]

Cycloadditions of Nitrile Oxide 2 to Allyl Ethers 3a—f Leading to 2-Isoxazolines 4a—f. As a standard procedure the reaction of **2** with **3a** is described below: To a solution of oxime **1** (0.39 g, 2 mmol) in DMF (4 ml) was added dropwise, at −20 °C in a period of 5 min, a solution of NBS (0.712 g, 4 mmol) in DMF (4 ml). The mixture was stirred at −20 °C for 1 h and then at 0 °C for 30 min. After cooled to −20 °C again, a solution of triethylamine (0.202 g, 0.28 ml, 2 mmol) in dry diethyl ether (4 ml) and then a solution of allyl ether **3a** (1.422 g, 10 mmol) in diethyl ether (4 ml) were added. The resulting mixture was stirred at room temperature for 18 h and then diluted with dichloromethane (250 ml). This solution was washed with water (200 ml×3), dried over magnesium sulfate, and evaporated in vacuo. The residue was chromatographed over silica gel by using ethyl acetate to give **4a** (0.419 g, 62%) as a mixture of two diastereomers. These 3-phosphorylmethyl-2-isoxazolines **4** except for **4e** are too hygroscopic to provide authentic samples for analyses. They were used in subsequent reactions without further purification.

4a: Pale yellow liquid; IR (neat) 1620, 1250, 1025, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.32 (6H, t, J=7.0 Hz, OEt), 1.4—1.9 (2H, m, THP), 2.93 (2H, d, $J_{H\text{-}P}$=22.0 Hz, CH_2P), 2.7—3.4 (2H, m, 4-H), 3.4—3.9 (4H, THP and CH_2OTHP), 4.12 (4H, dq, $J_{H\text{-}P}$=7.5 and J=7.0 Hz, OEt), 4.62 (1H, m, THP), and 4.77 (1H, m, 5-H); ^{13}C NMR ($CDCl_3$) δ=16.18 (dq, $J_{C\text{-}P}$=5.9 Hz, OEt), 19.00, 19.12, 25.18 (each t, THP), 26.06 (dt, $J_{C\text{-}P}$=141.2 Hz, CH_2P), 30.24 (t, THP), 39.30, 39.59 (each t, 4-C), 61.89, 62.06 (each t, CH_2OTHP), 62.42 (dt, $J_{C\text{-}P}$=5.9 Hz, OEt), 67.71, 68.24 (each t, THP), 79.54 (d, 5-C), 98.83, 99.01 (each d, THP), and 151.27 (d, $J_{C\text{-}P}$=7.4 Hz, 3-C); MS *m/z* (rel intensity, %) 252 (5), 251 (16), 220 (M^+-CH_2THP, base peak), 164 (24), 153 (30), and 83 (73).

4b: A similar procedure using oxime **1** (0.39 g, 2 mmol), NBS (0.712 g, 4 mmol), triethylamine (0.202 g, 0.28 ml, 2 mmol), and allyl ether **3b** (1.562 g, 10 mmol) gave **4b** (0.533 g, 76%) as a mixture of four diastereomers after column chromatography over silica gel with ethyl acetate. Pale yellow liquid; IR (neat) 1620, 1255, 1025, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.15, 1.18 (3H, each d, J=6.5 Hz, Me), 1.32 (6H, t, J=7.0 Hz, OEt), 1.3—1.9 (6H, m, THP), 2.9—3.2 (2H, m, 4-H), 2.93 (2H, d, $J_{H\text{-}P}$=22.0 Hz, CH_2P), 3.3—4.1 (3H, m, THP and CHOTHP), 4.13 (4H, dq, $J_{H\text{-}P}$=7.5 and J=7.0 Hz, OEt), 4.50 (1H, m, 5-H), and 4.68 (1H, m, THP), ^{13}C NMR ($CDCl_3$) δ=13.88, 15.24, 17.00, 18.06 (each q, Me), 16.35 (dq, $J_{C\text{-}P}$=5.9 Hz, OEt), 19.35, 19.82, 25.47 (each t, THP), 26.24 (dt, $J_{C\text{-}P}$=141.2 Hz, CH_2P), 30.94 (t, THP), 37.65, 38.30, 39.18 (each t, 4-C), 62.59 (dt, $J_{C\text{-}P}$=5.9 Hz, OEt), 69.06, 71.42, 73.71, 74.12 (each d, CHOTHP), 82.95, 83.83, 84.06, 84.42 (each d, 5-C), 95.31, 96.42, 99.83, 100.24 (each d, THP), and 151.51 (d, $J_{C\text{-}P}$=7.4 Hz, 3-C); MS *m/z* (rel intensity, %) 304 (1), 220 ($M^+-MeCHOTHP$, 43), 193 (31), 178 (26), 164 (20), 153 (77), 125 (28), and 85 (base peak).

4c: A similar procedure using oxime **1** (0.39 g, 2 mmol), NBS (0.712 g, 4 mmol), triethylamine (0.202 g, 0.28 ml, 2 mmol), and allyl ether **3c** (1.682 g, 10 mmol) gave **4c** (0.529 g, 73%) as a mixture of three diastereomers after column chromatography over silica gel with ethyl acetate. Pale yellow liquid; IR (neat) 1620, 1255, 1025, and 810 cm^{-1}, ^1H NMR ($CDCl_3$) δ=0.92, 0.99 (3H, each t, J=6.5 Hz, Et), 1.32 (6H, t, J=7.0 Hz, OEt), 1.3—1.9 (6H, m, THP), 2.93 (2H, d, $J_{H\text{-}P}$=22.0 Hz, CH_2P), 2.9—3.3 (2H, m, 4-H), 3.3—4.0 (5H, m, THP, CHOTHP, and Et), 4.13 (4H, dq, $J_{H\text{-}P}$=7.0 Hz, OEt), and 4.4—4.9 (2H, m, 5-H and THP), ^{13}C NMR ($CDCl_3$) δ=9.06, 10.12 (each q, Et), 16.41 (dq, $J_{C\text{-}P}$=5.9 Hz, OEt),

19.71, 20.12 (each t, THP), 22.06, 23.30 (each t, Et), 25.53 (t, THP), 26.35 (dd, J_{C-P}=141.2 Hz, CH_2P), 31.06 (t, THP), 37.36 (t, 4-C), 38.41, 39.47 (each t, 4-C), 62.45 (dt, J_{C-P}=4.4 Hz, OEt), 62.59 (dt, J_{C-P}=2.9 Hz, OEt), 63.18, 63.36 (each t, THP), 77.65, 78.12 (each d, CHOTHP), 81.71, 82.01, 83.54 (each d, 5-C), 97.54, 99.65, 100.30 (each d, THP), and 151.75 (d, J_{C-P}=10.3 Hz, 3-C); MS *m/z* (rel intensity, %) 280 (1), 279 (1), 220 (M^+−EtCHOTHP, 37), 193 (37), 178 (27), 164 (25), 153 (78), 125 (26), and 85 (base peak).

4d: A similar procedure using oxime **1** (0.39 g, 2 mmol), NBS (0.712 g, 4 mmol), triethylamine (0.202 g, 0.28 ml, 2 mmol), and allyl ether **3d** (1.562 g, 10 mmol) gave **4d** (0.467 g, 67%) as a mixture of two diastereomers after column chromatography over silica gel with ethyl acetate. Pale yellow liquid; IR (neat) 1620, 1250, 1020, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.32 (6H, t, *J*=7.0 Hz, OEt), 1.36 (3H, s, Me), 1.4—1.9 (6H, m, THP), 2.6—3.2 (2H, m, 4-H), 2.81 (2H, d, J_{H-P}=21.5 Hz, CH_2P), 3.3—3.9 (4H, m, THP and CH_2OTHP), 4.13 (4H, dq, J_{H-P}=7.5 and *J*=7.0 Hz, OEt), and 4.63 (1H, m, THP); ^{13}C NMR ($CDCl_3$) δ=16.41 (dq, J_{C-P}=5.9 Hz, OEt), 19.18, 19.35 (each t, THP), 23.06, 23.18 (each q, Me), 26.59 (dt, J_{C-P}=141.2 Hz, CH_2P), 30.47 (t, THP), 45.00, 45.47 (each t, 4-C), 61.89, 62.18 (each t, THP), 62.53 (dt, J_{C-P}=5.9 Hz, OEt), 71.06, 71.36 (each t, CH_2OTHP), 86.18, 86.42 (each s, 5-C), 98.83, 99.18 (each d, THP), and 151.42 (d, J_{C-P}=8.8 Hz, 3-C); MS *m/z* (rel intensity, %) 234 (M^+−CH_2OTHP, base peak), 206 (24), 178 (58), 152 (35), and 85 (49).

4e: To a solution of oxime **1** (0.585 g, 3 mmol) in dry DMF (6 ml) was added NBS (1.068 g, 6 mmol) in DMF (6 ml) at −20 °C in a period of 5 min. The mixture was stirred at −20 °C for 1 h and then at 0 °C for 30 min. After diluted with dry diethyl ether (6 ml), triethylamine (0.304 g, 0.42 ml, 3 mmol) and then allyl ether **3e** (3.845 g, 15 mmol in diethyl ether (6 ml)) were added. The mixture was stirred at room temperature for 18 h and diluted with dichloromethane (200 ml). The dichloromethane was washed with water (200 ml×3), dried over magnesium sulfate, and finally evaporated in vacuo. The residue was chromatographed over silica gel by using ethyl acetate to give **4e** (0.618 g, 46%) as a mixture of four diastereomers. Colorless viscous liquid; IR (neat) 1620, 1250, 1025, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.2—2.0 (12H, m, THP), 1.32 (6H, t, *J*=7.0 Hz, OEt), 2.6—3.2 (2H, m, CH_2P), 3.3—4.0 (5H, m, THP and 4-H), 4.13 (4H, dq, J_{H-P}=7.5 and *J*=7.0 Hz, OEt), and 4.32 (3H, m, THP and 5-H); ^{13}C NMR ($CDCl_3$) δ=16.41 (dq, J_{C-P}=5.9 Hz, OEt), 19.18, 19.41 (each t, THP), 25.44 (dt, J_{C-P}=145.6 Hz, CH_2P), 25.47, 30.53 (each t, THP), 50.36 (d, 4-C), 61.89, 62.30 (each t, CH_2OTHP), 65.30, 65.56 (each d, THP), 81.18, 81.36, 81.71, 81.95 (each d, 5-C), 98.99, 99.18 (each d, THP), 153.75 (d, J_{C-P}=10.3 Hz, 3-C), and 153.83 (d, J_{C-P}=5.9 Hz, 3-C); MS *m/z* (rel intensity, %) 366 (4), 281 (51), 264 (22), 251 (32), 250 (42), 234 (20), 233 (72), 232 (28), 220 (base peak), 178 (21), 152 (37), and 85 (92).

Found: C, 53.28; H, 8.14; N, 3.31%. Calcd for $C_{20}H_{36}O_8NP$: C, 53.44; H, 8.07; N, 3.12%.

4f: A similar procedure as employed for **4e** was applied to oxime **1** (0.39 g, 2 mmol), NBS (0.712 g, 4 mmol), triethylamine (0.202 g, 0.28 ml, 2 mmol), and allyl ether **3f** (1.823 g, 10 mmol) to give **4f** (0.2 g, 29%) as a mixture of two diastereomers. Yellow liquid; IR (neat) 1260, 1025, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.32 (6H, t, *J*=7.0 Hz, OEt), 1.0—2.1 (12H, m, THP and CH_2), 2.5—3.2 (3H, CH_2P and 4-H), 3.3—3.8 (4H, m, THP and CH_2OTHP), 4.14 (4H, dq, J_{H-P}=7.5 and *J*=7.0 Hz, OEt), and 4.65 (1H, m, THP); ^{13}C NMR ($CDCl_3$) *J*=16.43 (dq, J_{C-P}=6.1 Hz, OEt), 19.14, 19.34 (t, THP), 24.27 (t, 5-C), 25.12 (dt, J_{C-P}=140.4 Hz, CH_2P), 25.49, 30.47 (each t, THP), 37.21 (t, 4- and 6-C), 55.71, 56.05 (each d, 3a-C), 61.74, 62.43 (each dt, J_{C-P}=6.1 Hz, OEt), 62.74, 63.33 (each t, CH_2OTHP), 69.48, 69.68 (each t, THP), 97.31, 97.51 (each s, 6a-C), 98.78, 99.32 (each d, THP), and 153.17 (d, J_{C-P}=9.8 Hz, 3-C); MS *m/z* (rel intensity, %) 292 (10), 291 (18), 261 (16), 260 (base peak), 178 (45), 152 (34), 125 (30), 122 (26), and 85 (65).

Alkylation of 2-Isoxazolines 4c—d Leading to 4g—j. As a typical procedure the alkylation of **4c** with 1-iodooctane is presented as follows: To a solution of **4c** (0.321 g, 0.883 mmol) in dry THF (3 ml) was added at −78 °C butyllithium (15% in hexane, 0.55 ml, 0.883 mmol). After the mixture was stirred for 1 h at the same temperature, octyl iodide (0.424 g, 0.32 ml, 1.766 mmol) was added. The resulting mixture was stirred at 0 °C for 1 h and then at room temperature for 14 h. Saturated aqueous sodium chloride (30 ml) was added to the mixture and then extracted with dichloromethane (30 ml×3). The combined extracts were dried over magnesium sulfate and then chromatographed over silica gel by using hexane-ethyl acetate (1 : 1 v/v) to afford **4g** (0.267 g, 64%). The elution with ethyl acetate gave the starting **4c** (0.026 g, 8%).

4g (a mixture of four diastereomers): Colorless liquid; IR (neat) 1615, 1250, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.7—1.1 (6H, m, Et and *n*-C_8H_{17}), 1.1—2.0 (22H, m, Et, *n*-C_8H_{17}, and THP), 1.31 (6H, t, *J*=7.0 Hz, Et), 2.7—4.0 (6H, m, CH_2P, CHOTHP, THP, and 4-H), 4.11 (4H, dq, J_{H-P}=7.5 and *J*=7.0 Hz, OEt), and 4.4—4.9 (2H, m, THP and 5-H), ^{13}C NMR ($CDCl_3$) δ=9.06, 10.06 (each q, Et), 14.12 (q, *n*-C_8H_{17}), 16.47 (dq, J_{C-P}=5.9 Hz, OEt), 20.18, 22.71, 23.64, 25.53, 26.46, 27.65, 28.18, 29.30, 31.06, 31.88 (each t, CH_2 and THP), 34.53, 35.88, 36.59, 38.00 (each t, 4-C), 37.80 (dd, J_{C-P}=139.7 Hz, CHP), 62.59 (t, OEt), 63.24, 63.83 (each t, THP), 76.89, 78.01 (each d, EtCHOTHP), 81.59, 82.89, 83.36 (each d, 5-C), 97.42, 99.83, 100.18, 100.65 (each d, THP), and 155.77 (s, 3-C); MS *m/z* (rel intensity, %) 475 (M^+, 3), 391 (83), 332 (23), 331 (base peak), 263 (77), 165 (31), 152 (39), and 85 (66). HRMS Found: *m/z* 475.3049. Calcd for $C_{24}H_{46}NO_6P$: M, 475.3060.

4h: A similar procedure using **4c** (0.396 g, 1.09 mmol), butyllithium (15% in hexane, 0.68 ml, 1.09 mmol), and pentyl iodide (0.432 g, 0.28 ml, 2.18 mmol) gave **4h** (0.307 g, 65%) after silica-gel chromatography with hexane-ethyl acetate (1:1 v/v) and the starting **4c** (0.049 g, 12%) from the elution with ethyl acetate. **4h** (a mixture of five diastereomers): Colorless liquid; IR (neat) 1610, 1250, 1025, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.7—1.2 (6H, m, OEt), 1.2—2.0 (16H, m, *n*-C_5H_{11}, Et, and THP), 1.31 (6H, t, *J*=7.0 Hz, OEt), 2.8—4.0 (6H, m, PCH, CHOTHP, THP, and 4-H), 4.11 (dq, J_{H-P}=7.5 and *J*=7.0 Hz, OEt), and 4.4—4.9 (2H, m, THP and 5-H); ^{13}C NMR ($CDCl_3$) δ=9.03, 10.01, 10.16 (each q, Et), 13.96 (q, *n*-C_5H_{11}), 16.43 (qd, J_{C-P}=6.1 Hz, OEt), 19.72, 19.87, 20.12, 22.12, 22.41, 23.14, 23.63, 25.54, 26.46, 26.61, 27.29, 27.88, 31.02, 31.30 (each t, CH_2 and THP), 34.52, 36.57 (each t, 4-C), 37.79 (dt, J_{C-P}=139.2 Hz, CHP), 62.57 (dt, J_{C-P}=6.1 Hz, OEt), 63.04, 63.82 (each t, THP), 76.86, 77.68, 77.98 (each d, CHOTHP), 81.54, 83.15, 83.35 (each d, 5-C), 97.41, 97.51, 99.80, 100.14, 100.59 (each d, THP), and 155.46 (s, 3-C); MS *m/z* (rel intensity, %) 349 (4), 331 (7), 290 (24), 289 (base peak), 222 (85), 165 (42), and 85 (79).

Found: C, 57.90; H, 9.17; N, 3.27%. Calcd for $C_{21}H_{40}NO_6P$: C, 58.18; H, 9.39; N, 3.23%.

4i: A similar perocedure using **4d** (0.5 g, 1.43 mmol), butyllithium (15% in hexane, 0.89 ml, 1.43 mmol), and pentyl iodide (0.567 g, 0.37 ml, 2.862 mmol) afforded **4i** (0.352 g, 59%) after silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) together with the starting **4d** (0.054 g, 11%) from the fraction eluted with ethyl acetate. **4i** (a mixture of four diastereomers): Pale yellow viscous liquid; IR (neat) 1615, 1250, 1035, and 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.88 (3H, t, J=6.0 Hz, n-C_5H_{11}), 1.0—2.0 (14H, m, THP and n-C_5H_{11}), 1.32 (6H, t, J=7.0 Hz, OEt), 1.37 (3H, s, 5-Me), 2.5—3.9 (7H, m, THP, CH_2OTHP, CHP), 4.12 (4H, dq, J_{H-P}=7.5 and J=7.0 Hz, OEt), and 4.64 (1H, br s, THP); ^{13}C NMR ($CDCl_3$) δ=14.00 (q, n-C_5H_{11}), 16.47, (dq, J_{C-P}=5.9 Hz, OEt), 19.12, 19.35, 19.53, 22.41, 26.47, 27.24, 27.83 (each t, CH_2 and THP), 23.35 (q, 5-Me), 25.53, 30.36, 31.30 (each t, THP), 37.91 (dd, J_{C-P}=139.7 Hz, CHP), 42.36, 42.89, 43.24, 43.77 (each t, 4-C), 61.95 (dt, J_{C-P}=5.9 Hz, OEt), 62.45 (dt, J_{C-P}=7.4 Hz, OEt), 70.83, 71.24 (each t, CH_2OTHP), 85.77, 85.95, 86.06 (each s, 5-C), 98.60, 98.83, 99.12, 99.42 (each d, THP), and 155.12 (d, J_{C-P}=4.4 Hz, 3-C); MS m/z (rel intensity, %) 304 (M^+-CH_2OTHP, base peak) and 85 (21). Found: 56.97; H, 9.01; N, 3.36%. Calcd for $C_{20}H_{38}NO_6P$: C, 57.26; H, 9.13; N, 3.34%.

4j: A similar procedure using **4d** (0.5 g, 1.43 mmol), butyllithium (15% in hexane, 0.89 ml, 1.43 ml), and benzyl bromide (0.49 g, 0.34 ml, 2.86 mmol) gave **4j** (0.41 g, 65%) after silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) together with the starting **4d** (0.043 g, 9%) from the fraction eluted with ethyl acetate. As **4j** was hygroscopic, it was used for subsequent reactions without further purification. **4j** (a mixture of four diastereomers): Pale yellow viscous liquid; IR (neat) 1610, 1250, 1030, and 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.11, 1.16, 1.26, 1.29 (3H, each s, 5-Me), 1.32 (6H, t, J=7.0 Hz, OEt), 1.3—1.9 (6H, m, THP), 2.3—3.9 (6H, m, CHP, CH_2OTHP, THP, and 4-H), 4.13 (4H, dq, J_{H-P}=7.5 and J=7.0 Hz, OEt), 4.4—4.7 (1H, m, THP), and 7.29 (5H, br s, Ph); ^{13}C NMR ($CDCl_3$) δ=16.47 (dq, J_{C-P}=5.9 Hz, OEt), 19.30 (t, THP), 23.00 (q, 5-Me), 25.47, 30.41 (t, THP), 32.71 (t, CH_2Ph), 39.36 (dd, J_{C-P}=138.2 Hz, CHP), 43.18, 43.47, 43.94, 44.06 (each t, 4-C), 61.95 (t, THP), 62.68 (dt, J_{C-P}=7.4 Hz, OEt), 70.24, 70.48, 71.01 (each t, CH_2OTHP), 85.89, 86.12 (each s, 5-C), 98.95 (d, THP), 126.95, 128.72, 128.89 (each d), 137.89, 138.54 (each s), 154.51, and 154.80 (d, J_{C-P}=7.4 Hz, 3-C); MS m/z (rel intensity, %) 325 (15), 324 (M^+-CH_2OTHP, 87), 296 (22), 268 (30), 242 (21), 186 (25), 185 (21), 144 (31), 138 (24), 109 (26), 105 (21), 104 (40), 103 (35), 91 (base peak), 85 (98), 81 (36), and 77 (24).

Conversion of 2-Isoxazolines 4a—j to 2-(1-Phosphorylalkyl)-furans 5a—j. As a typical procedure the conversion of **4a** into **5a** is described: A mixture of 2-isoxazoline **4a** (0.173 g, 0.516 mmol), Raney Ni W-2 (suspension in ethanol, 0.5 ml), and boric acid (0.066 g, 1.06 mmol) in aqueous ethanol (17%, 3 ml) was stirred under hydrogen atmosphere at room temperature for 13.5 h. Insoluble material was filtered through Celite and washed with water and then dichloromethane. The combined filtrate and washings were extracted with dichloromethane (30 ml×3). The dichloromethane was dried over magnesium sulfate and evaporated in vacuo. The residue was heated with sodium acetate (0.179 g, 2.185 mmol) in acetic acid (1 ml) at 100 °C for 2 h. The reaction mixture was cooled to room temperature, diluted with dichloromethane (90 ml), washed with water (50 ml) and then saturated sodium hydrogencarbonate (50 ml), and finally dried over magnesium sulfate. The solvent was evaporated in vacuo and the residue was chromatographed over silica gel by using hexane-ethyl acetate (1 : 5 v/v) to give **5a** (0.067 g, 60%).

The same product **5a** was obtained in 77% yield (0.039 g) by a similar procedure (100 °C for 3 h) using purified **6** (0.079 g, 0.233 mmol), sodium acetate (0.095 g, 1.165 mmol), and acetic acid (0.5 ml). The preparation of **6** is described later.

5a: Pale yellow liquid; IR (neat) 3000, 1595, 1250, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.26 (6H, t, J=7.0 Hz, OEt), 3.21 (2H, d, J_{H-P}=21.5 Hz, CH_2P), 4.04 (4H, dq, J_{H-P}=8.0 and J=7.0 Hz, OEt), 6.1—6.4 (2H, m, 3- and 4-H), and 7.31 (1H, m, 5-H); ^{13}C NMR ($CDCl_3$) δ=16.41 (dq J_{C-P}=4.9 Hz, OEt), 26.78 (dt, J_{C-P}=142.8 Hz, CH_2P), 62.45 (dt, J_{C-P}=7.3 Hz, OEt), 108.45 (dd, J_{C-P}=7.3 Hz, 3-C), 111.01 (dd, J_{C-P}=3.7 Hz, 4-C), 142.16 (dd, J_{C-P}=3.7 Hz, 5-C), and 145.95 (d, J_{C-P}=9.8 Hz, 2-C); MS m/z (rel intensity, %) 218 (M^+, 15), 162 (21), 109 (19), and 81 (base peak). HRMS Found: m/z 218.0704. Calcd for $C_9H_{15}O_4P$: M, 218.0707.

5b: A similar procedure using 1) **4b** (0.215 g, 0.615 mmol), Raney Ni W-2 in ethanol (0.6 ml), boric acid (0.078 g, 1.261 mmol), and aqueous ethanol (17%, 3.6 ml) at room temperature for 13 h, 2) sodium acetate (0.252 g, 3.075 mmol) and acetic acid (1.3 ml) at 100 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 3 v/v) gave **5b** (0.077 g, 54%): Pale yellow liquid; IR (neat) 3000, 1565, 1250, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.27 (6H, t, J=7.0 Hz, OEt), 2.24 (3H, d, J=1.7 Hz, 5-Me), 3.17 (2H, d, J_{H-P}=20.5 Hz, CH_2P), 4.06 (4H, dq, J_{H-P}=8.0 and J=7.0 Hz, OEt), 5.88 (1H, m, 4-H), and 6.08 (1H, t, J_{H-P}=J=3.4 Hz, 3-H), ^{13}C NMR ($CDCl_3$) δ=13.41 (q, 5-Me), 16.27 (dq, J_{C-P}=7.4 Hz, OEt), 26.65 (dt, J_{C-P}=144.1 Hz, CH_2P), 62.27 (dt, J_{C-P}=7.4 Hz, OEt), 106.71 (dd, J_{C-P}=2.9 Hz, 4-C), 109.01 (dd, J_{C-P}=8.8 Hz, 3-C), 143.66 (d, J_{C-P}=8.8 Hz, 2-C), and 151.54 (d, J_{C-P}=2.9 Hz, 5-C); MS m/z (rel intensity, %) 232 (M^+, 4) and 95 (base peak). HRMS Found: m/z 232.0887. Calcd for $C_{10}H_{17}O_4P$: M, 232.0863.

5c: A similar procedure using 1) **4c** (0.215 g, 0.615 mmol), Raney Ni W-2 in ethanol (0.6 ml), boric acid (0.075 g, 1.207 mmol), and aqueous ethanol (17%, 3.6 ml) at room temperature for 13 h, 2) sodium acetate (0.252 g, 2.945 mmol) and acetic acid (1.3 ml) at 100 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 3 v/v) gave **5c** (0.084 g, 60%): pale yellow liquid; IR (neat) 3000, 1560, 1250, 1025, and 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.18 (3H, t, J=8.0 Hz, Et), 1.27 (6H, t, J=7.0 Hz, OEt), 2.60 (2H, q, J=8.0 Hz, Et), 3.16 (2H, d, J_{H-P}=21.0 Hz, CH_2P), 4.05 (4H, dq, J_{C-P}=8.0 and 7.0 Hz, OEt), 5.88 (1H, d, J=3.5 Hz, 4-H), and 6.09 (1H, t, J_{H-P}=J= 3.5 Hz, 3-H); ^{13}C NMR ($CDCl_3$) δ=12.24 (q, Et), 16.35 (dp, J_{C-P}=5.9 Hz, OEt), 21.35 (t, Et), 26.74 (dt, J_{C-P}=142.7 Hz, CH_2P), 62.33 (dt, J_{C-P}=7.4 Hz, OEt), 105.24 (dd, J_{C-P}=2.9 Hz, 4-C), 108.86 (dd, J_{C-P}=7.4 Hz, 3-C), 143.69 (d, J_{C-P}=10.3 Hz, 2-C), and 157.30 (s, 5-C); MS m/z (rel intensity, %), 246 (M^+, 4), 109 (base peak), 94 (12), and 81 (11). HRMS Found: m/z 246.1017. Calcd for $C_{11}H_{19}O_4P$: M, 246.1020.

5d: A similar procedure using 1) **4d** (2.48 g, 7.1 mmol), Raney Ni W-2 in ethanol (6 ml), boric acid (4.35 g, 71 mmol), and aqueous ethanol (17%, 41 ml) at room temperature for 13.5 h, 2) sodium acetate (2.91 g, 35.5 mmol) and acetic acid (16 ml) at 100 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) afforded **5d**

(1.16 g, 70%): Pale yellow liquid; IR (neat) 3000, 1620, 1240, 1020, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.27 (6H, t, J=7.0 Hz, OEt), 1.96 (3H, d, J=1.0 Hz, Me), 3.14 (2H, d, J_{H-P}=21.5 Hz, CH_2P), 4.05 (4H, dq, J_{H-P}=8.0 and J=7.0 Hz, OEt), 6.08 (1H, d, J_{H-P}=3.5 Hz, 3-H), and 7.06 (1H, m, 5-H); ^{13}C NMR ($CDCl_3$) δ=9.77 (q, Me), 16.41 (dq, J_{C-P}=5.9 Hz, OEt), 26.83 (dd, J_{C-P}=144.1 Hz, CH_2P), 62.42 (dt, J_{C-P}=5.9 Hz, OEt), 111.15 (dd, J_{C-P}=7.4 Hz, 3-C), 121.30 (d, J_{C-P}=2.9 Hz, 4-C), 138.78 (dd, J_{C-P}=2.9 Hz, 5-C), and 145.77 (d, J_{C-P}=8.8 Hz, 2-C); MS m/z (rel intensity, %) 232 (M^+, 10), 176 (10), 96 (12), 95 (base peak), and 80 (11). HRMS Found: m/z 232.0867. Calcd for $C_{10}H_{17}O_4P$: M, 232.0863.

5e: A similar procedure using **4e** (0.134 g, 0.298 mmol), Raney Ni W-2 in ethanol (0.3 ml), boric acid (0.038 g, 0.611 mmol), and aqueous ethanol (17%, 1.8 ml) at room temperature for 14 h gave a hydrogenated product (0.11 g). This crude product was added to aqueous THF (50%, 1 ml) containing *p*-toluenesulfonic acid (0.028 g, 0.149 mmol) and the mixture was heated at 70 °C for 6.5 h. After an additional *p*-toluenesulfonic acid (0.028 g, 0.149 mmol) was added, heating was continued at the same temperature for 1.5 h. To the cooled mixture was added saturated aqueous sodium hydrogencarbonate (20 ml), and extracted with ethyl acetate (30 ml×3). The combined extracts were similarly treated and chromatographed over silica gel with hexane-ethyl acetate (1 : 1 v/v) to give **5e** (0.03 g, 41%): Colorless liquid; IR (neat) 3400, 3000, 1510, 1240, 1025, 970, and 800 cm^{-1}. ^1H NMR ($CDCl_3$) δ=1.26 (6H, t, 7.0 Hz, OEt), 3.28 (2H, d, J_{H-P}=20.8 Hz, CH_2P), 4.00 (4H, dq, J_{H-P}=8.0 and J=7.0 Hz, OEt), 4.30 (1H, br s, OH), 4.44 (2H, s, CH_2OH), 6.38 (1H, d, J=1.8 Hz, 4-H), and 7.28 (1H, dd, J_{H-P}=3.5 and J=1.8 Hz, 5-H); ^{13}C NMR ($CDCl_3$) δ=16.35 (dq, J_{C-P}=5.9 Hz, OEt), 25.62 (dt, J_{C-P}=142.7 Hz, CH_2P), 56.06 (t, CH_2OH), 62.95 (dt, J_{C-P}=5.9 Hz, OEt), 112.39 (dd, J_{C-P}=4.4 Hz, 4-C), 141.75 (dd, J_{C-P}= 4.4 Hz, 5-C), and 142.04 (d, J_{C-P}=10.3 Hz, 2-C); MS m/z (rel intensity, %) 248 (M^+, 6), 153 (21), 112 (52), 111 (52), 109 (75), 94 (34), 83 (69), 81 (70), 65 (25), and 56 (base peak). HRMS Found: m/z 248.0808. Calcd for $C_{10}H_{17}O_5P$: M, 248.0813.

5f: A procedure similar to that employed for **5a** using 1) **4f** (0.17 g, 0.494 mmol), Raney Ni W-2 in ethanol (0.5 ml), boric acid (0.063 g, 1.013 mmol), and aqueous ethanol (17%, 2.4 ml) at room temperature for 15 h, 2) sodium acetate (0.203 g, 2.47 mmol) and acetic acid (1 ml) at 90 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 3 v/v) gave **5f** (0.032 g, 25%): Pale yellow liquid; IR (neat) 2900, 1650, 1250, 1025, and 830 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.27 (6H, t, J=7.0 Hz, OEt), 2.1—2.7 (6H, m, CH_2), 3.14 (2H, d, J_{H-P}=20.5 Hz, CH_2P), 4.05 (4H, dq, J_{H-P}=8.0 and J=7.0 Hz, OEt), and 6.94 (1H, m, 5-H); MS m/z (rel intensity, %) 258 (M^+, 33), 121 (63), 120 (base peak), and 91 (25). HRMS Found: m/z 258.1019. Calcd for $C_{12}H_{19}O_4P$: M, 258.1020.

5g: A similar procedure using 1) **4g** (0.188 g, 0.395 mmol), Raney Ni W-2 in ethanol (0.4 ml), boric acid (0.05 g, 0.81 mmol), and aqueous ethanol (17%, 3 ml) at room temperature for 14 h, 2) sodium acetate (0.162 g, 1.975 mmol) and acetic acid (1 ml) at 100 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 5 v/v) gave **5g** (0.09 g, 64%): Pale yellow liquid; IR (neat) 2920, 1555, 1250, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.86 (3H, t, J=7.0 Hz, Et), 1.0—1.4 (21H, m, n-C_8H_{17} and OEt), 1.7—2.1 (2H, m, CH_2CHP), 2.60 (2H, q, Et), 3.11 (1H, ddd, J_{H-P}=23.0, J=9.0, and 6.0 Hz, CHP), 3.7—4.2 (4H, m, OEt), 5.88 (1H, d, J=3.2 Hz, 4-H), and 6.08 (1H, t, J_{H-P}=J=3.2 Hz, 3-H); ^{13}C NMR ($CDCl_3$) δ=12.29 (q, Et), 14.06 (q, n-C_8H_{17}), 16.41 (dq, J_{C-P}=5.9 Hz, OEt), 21.47, 22.70, 27.53, 28.18, 28.53, 28.65, 29.24 (each t, n-C_8H_{17}), 31.88 (t, Et), 38.59 (dd, J_{C-P}=141.2 Hz, CHP), 62.45, 62.93 (each dt, J_{C-P}=7.4 Hz, OEt), 105.13 (dd, J_{C-P}=2.9 Hz, 4-C), 108.45 (dd, J_{C-P}=7.4 Hz, 3-C), 148.48 (d, J_{C-P}=8.8 Hz, 2-C), and 157.07 (d, J_{C-P}=2.9 Hz, 5-C); MS m/z (rel intensity, %) 358 (M^+, 34), 221 (base peak), 155 (66), 127 (41), 110 (41), 99 (57), 85 (28), and 81 (21). Found: m/z 358.2288. Calcd for $C_{19}H_{35}O_4P$: M, 358.2271.

5h: A similar procedure using 1) **4h** (0.198 g, 0.457 mmol), Raney Ni W-2 in ethanol (0.5 ml), boric acid (0.283 g, 4.57 mmol), and aqueous ethanol (17%, 2.4 ml) at room temperature for 20 h, 2) sodium acetate (0.187 g, 2.285 mmol) and acetic acid (1 ml) at 100 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) gave **5h** (0.092 g, 64%): Pale yellow liquid; IR (neat) 2940, 1555, 1250, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.85 (3H, t, J=7.0 Hz, Et), 1.0—1.4 (15H, m, OEt and n-C_5H_{11}), 1.7—2.1 (2H, m, CH_2CHP), 2.60 (2H, q, J=7.0 Hz, Et), 3.11 (1H, ddd, J_{H-P}=23.0, J=9.0, and 6.0 Hz, CHP), 3.7—4.3 (4H, m, OEt), 5.89 (1H, d, J=3.2 Hz, 4-H), and 6.08 (1H, t, J_{H-P}=3.2 Hz, 3-H); ^{13}C NMR ($CDCl_3$) δ=12.24 (q, Et), 13.94 (q, n-C_5H_{11}), 16.38 (dq, J_{C-P}=4.4 Hz, OEt), 21.41, 22.35 (each t, n-C_5H_{11}), 27.44 (dt, J_{C-P}=13.2 Hz, n-C_5H_{11}), 28.53 (dt, J_{C-P}=2.9 Hz, n-C_5H_{11}), 31.36 (t, Et), 38.53 (dd, J_{C-P}=141.2 Hz, CHP), 62.03 (dt, J_{C-P}=7.4 Hz, OEt), 62.36 (dt, J_{C-P}=8.8 Hz, OEt), 105.06 (dd, J_{C-P}=2.9 Hz, 4-C), 108.39 (dd, J_{C-P}=7.4 Hz, 3-C), 148.42 (d, J_{C-P}=8.8 Hz, 2-C), and 157.07 (d, J_{C-P}=2.9 Hz, 5-C); MS m/z (rel intensity, %) 316 (M^+, 13), 179 (base peak), and 110 (66). HRMS Found: m/z 316.1806. Calcd for $C_{16}H_{29}O_4P$: M, 316.1802.

5i: A similar procedure using 1) **4i** (0.33 g, 0.787 mmol), Raney Ni W-2 (0.8 ml), boric acid (0.1 g, 1.613 mmol), and aqueous ethanol (17%, 4.8 ml) at room temperature for 15 h, 2) sodium acetate (0.323 g, 3.935 mmol) and acetic acid (1.7 ml) at 100 °C for 0.3 h, and silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) afforded **5i** (0.062 g, 26%): Colorless liquid; IR (neat) 1610, 1250, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.85 (3H, t, J=6.0 Hz, n-C_5H_{11}), 1.1—2.1 (8H, m, n-C_5H_{11}), 1.22, 1.28 (6H, m, OEt), 1.99 (3H, s, 4-Me), 2.10 (1H, ddd, J_{H-P}=23.0, J=9.0, and 6.0 Hz, CHP), 3.7—4.2 (4H, m, OEt), 6.09 (1H, d, J_{H-P}=4.0 Hz, 3-H), and 7.09 (1H, m, 5-H); ^{13}C NMR ($CDCl_3$) δ=9.82 (q, 4-Me), 14.00 (q, n-C_5H_{11}), 16.41 (dq, J_{C-P}=5.9 Hz, OEt), 22.41 (t, n-C_5H_{11}), 27.53 (dt, J_{C-P}=14.7 Hz, n-C_5H_{11}), 28.15 (dt, J_{C-P}=16.2 Hz, n-C_5H_{11}), 31.41 (t, n-C_5H_{11}), 38.68 (dd, J_{C-P}=139.7 Hz, CHP), 62.09 (dt, J_{C-P}=7.4 Hz, OEt), 62.50 (dt, J_{C-P}=7.4 Hz, n-C_5H_{11}), 110.74 (dd, J_{C-P}=7.4 Hz, 3-C), 121.19 (s, 4-C), 138.54 (dd, J_{C-P}=2.9 Hz, 5-C), and 150.48 (d, J_{C-P}=8.8 Hz, 2-C); MS m/z (rel intensity, %) 302 (M^+, 32), 232 (27), 165 (base peak), 164 (21), and 95 (92). HRMS Found: m/z 302.1656. Calcd for $C_{15}H_{27}O_4P$: M, 302.1645.

5j: A similar procedure using 1) **4j** (0.395 g, 0.899 mmol), Raney Ni W-2 (0.9 ml), boric acid (0.114 g, 1.843 mmol), and aqueous ethanol (17%, 5.4 ml) at room temperature for 15 h, 2) sodium acetate (0.369 g, 4.495 mmol) and acetic acid (2 ml) at 100 °C for 30 min, and silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) gave **5j** (0.045 g, 16%): Colorless liquid; IR (neat) 3000, 1610, 1250, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.22, 1.28 (6H, m,

OEt), 1.92 (3H, s, 4-Me), 3.0—3.6 (3H, m, $PhCH_2$ and CHP), 3.7—4.2 (4H, m, OEt), 6.01 (1H, d, J_{H-P}=3.5 Hz, 3-H), and 6.9—7.3 (6H, m, 5-H and Ph); ^{13}C NMR ($CDCl_3$) δ=9.29 (q, 4-Me), 15.94 (dq, J_{C-P}=5.9 Hz, OEt), 34.18 (t, CH_2), 40.24 (dd, J_{C-P}=141.2 Hz, CHP), 61.74 (dt, J_{C-P}=7.4 Hz, OEt), 111.15 (dd, J_{C-P}=7.4 Hz, 3-C), 120.57 (d, J_{C-P}=4.4 Hz, 4-C), 126.07, 127.95, 128.36 (each d), 138.24 (dd, J_{C-P}=2.9 Hz, 5-C), 139.07 (s), and 148.83 (d, J_{C-P}=8.8 Hz, 2-C); MS *m/z* (rel intensity, %) 322 (M^+, 50), 231 (96), 185 (60), 184 (99), 155 (21), 141 (34), 129 (25), 128 (23), 121 (47), 116 (23), 110 (46), 95 (74), 91 (base peak), and 81 (51). HRMS Found: *m/z* 322.1339. Calcd for $C_{17}H_{23}O_4P$: M, 322.1333.

Alkylation of 2-(Phosphorylmethyl)furan 5d Leading to 2-(1-Phosphorylalkyl)furans 5i, j. To a solution of **5d** (0.241 g, 1.033 mmol) in dry THF (3 ml) was added at −78 °C butyllithium (15% in hexane, 0.65 ml, 1.033 mmol). After 1 h at −78 °C under nitrogen, pentyl iodide (0.205 g, 0.13 ml, 1.033 mmol) was added and the mixture was stirred for 5 h at the same temperature. Aqueous THF (1 : 1 v/v, 50 ml) was added slowly and the product was extracted with dichloromethane (30 ml×3). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed over silica gel by using hexane-ethyl acetate (2 : 1 v/v) to give **5i** (0.274 g, 88%) and a later fraction afforded the starting **5d** (0.013 g, 5%). Spectral data of **5i** is presented above.

A similar procedure using **5d** (0.197 g, 0.848 mmol), butyllithium (15% in hexane, 0.53 ml, 0.848 mmol), and benzyl bromide (0.145 g, 0.1 ml, 0.848 mmol) in THF (3 ml) was followed by silica-gel column chromatography with hexane-ethyl acetate (1 : 1 v/v) to give **5j** (0.239 g, 87%).

Reductive Ring-Opening of 4a into 6. A mixture of **4a** (0.202 g, 0.614 mmol), Raney Ni W-2 (0.5 ml), and boric acid (0.078 g, 1.259 mmol) in aqueous ethanol (17%, 17.5 ml) was stirred under hydrogen atmosphere at room temperature for 19 h. After another portion of Raney Ni (0.5 ml) was added, stirring was continued also under hydrogen for additional 19.5 h. All the insoluble material was filtered through Celite and washed with water and then dichloromethane. The combined filtrate and washings were extracted with dichloromethane (50 ml×3). The extract was dried over magnesium sulfate and evaporated in vacuo. The residue (0.181 g, 87%) was chromatographed over silica gel by using ethyl acetate to give **6** (0.095 g) as a mixture of two diastereomers. Colorless liquid; IR (neat) 3400, 1710, 1250, 1025, and 810 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.32 (6H, t, J=7.0 Hz, OEt), 1.4—1.96 (6H, m, THP), 2.80 (2H, d, J=6.5 Hz, 3-H), 3.14 (2H, d, J_{H-P}=22.5 Hz, CH_2P), 3.3—4.2 (6H, m, THP, CH_2OTHP, OH, and CHOH), 4.12 (4H, dq, J_{H-P}=8.0 and J=7.0 Hz, OEt), 4.54 (1H, m, THP), ^{13}C NMR ($CDCl_3$) δ=16.32 (dq, J_{C-P}=7.4 Hz, OEt), 19.82, 25.35, 30.65 (each t, THP), 43.12 (dt, J_{C-P}=126.5 Hz, CH_2P), 47.71, 47.94 (each t, 3-C), 60.83 (t, CH_2OTHP), 62.77 (dt, J_{C-P}=5.9 Hz, OEt), 67.01 (d, CHOH), 71.71, 72.01 (each t, THP), 99.89, 100.01 (each d, THP), and 201.71 (d, J_{C-P}=5.9 Hz, CO); MS *m/z* (rel intensity, %) 266 (1), 226 (12), 224 (39), 223 (M^+-CH_2OTHP, base peak), 219 (43), 195 (20), 152 (27), and 85 (42).

As this compound **6** is too hygroscopic to be submitted for analysis, it was converted into *O*-silyl derivative according to the following procedure: To a solution of **6** (0.16 g, 0.47 mmol) in dry DMF (1 ml) were added *t*-butyldimethylsilyl chloride (0.086 g, 0.568 mmol) and imidazole (0.081 g, 1.183 mmol). The mixture was stirred at room temperature for 15.5 h. Diethyl ether (100 ml) was added, the resulting mixture was washed with aqueous sodium chloride (50 ml×3), dried over magnesium sulfate, and then evaporated in vacuo. The residue was chromatographed over silica gel by using hexane-ethyl acetate (1 : 2 v/v) to give ethyl 4-(*t*-butyldimethylsilyloxy)-2-oxo-5-(2-tetrahydropyranyloxy)pentylphosphonate (0.171 g, 80%). Colorless liquid; IR (neat) 1720, 1250, 1030, 830, and 780 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.09 (6H, s, Me_2Si), 0.84 (6H, s, *t*-BuSi), 1.33 (6H, t, J=7.0 Hz, OEt), 1.4—1.7 (6H, THP), 2.7—2.9 (2H, m, 3-H), 3.11 (2H, d, J_{H-P}=22.5 Hz, CH_2P), 3.6—3.9 (4H, m, THP and CH_2OTHP), 4.12 (4H, dq, J_{H-P}=8.0, and 7.0 Hz, OEt), 4.22 (1H, m, 4-H), and 4.55 (1H, m, THP); ^{13}C NMR ($CDCl_3$) δ=−4.59, −4.88 (each q, Me_2Si), 16.35 (dq, J_{C-P}=5.9 Hz, OEt), 18.06 (s, *t*-BuSi), 19.24, 19.41, 25.47 (each t, THP), 25.88 (q, *t*-BuSi), 30.53 (t, THP), 43.77 (dt, J_{C-P}=126.5 Hz CH_2P), 49.24 (t, 3-C), 62.06, 62.59 (each dt, J_{C-P}=5.9 Hz, OEt), 62.48, 62.71 (each t, CH_2OTHP), 68.18, 68.36 (each d, 4-C), 71.24 (t, THP), 98.83 (d, THP), 200.72, and 200.83 (each d, J_{C-P}=2.9 Hz, CO); MS *m/z* (rel intensity, %) 395 (M^+-t-Bu, 10), 337 (14), 311 (56), 220 (11), 219 (base peak), 191 (15), 163 (12), 84 (20), and 75 (13). Found: C, 53.11; H, 9.15%. Calcd for $C_{20}H_{41}O_7PSi$: C, 53.08; H, 9.13%.

Reactions of 2-(Phosphorylmethyl)furan with Carbonyl Compounds Leading to 7b—h. To a solution of **5d** (0.232 g, 1 mmol) in dry THF (3 ml) was added butyllithium (15% in hexane, 0.63 ml, 1 mmol) at −78 °C. The mixture was stirred at the same temperature under nitrogen for 1 h and a carbonyl compound (1 to 1.5 mmol) was added. After 30 min at −78 °C, saturated ammonium chloride (20 ml) was added and extraction with dichloromethane (30 ml×3) followed. The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed over silica gel with hexane-ethyl acetate (2 : 1 v/v) as an eluent to give **7**. Further elution with hexane-ethyl acetate (1 : 1 v/v) recovered the unreacted **5d**. Amounts of the carbonyl compounds are as follows: benzaldehyde (1.5 mmol), butanal (1 mmol), cyclopentanone (1.5 mmol), cyclohexanone (1.2 mmol, reaction time: 2 h), 3-pentanone (1.5 mmol), 2-heptanone (1.5 mmol), 5-hexen-2-one (1.5 mmol).

These adducts **7** are too hygroscopic to be submitted for analyses except for **7e** and **7g**. Accordingly they were used in the subsequent olefination without further purification.

7b: (a 7 : 3 mixture of two diastereomers): Pale yellow viscous liquid; ^1H NMR ($CDCl_3$) δ=1.0—1.4 (6H, m, OEt), 1.86 (7/10×3H, s, 4-Me), 1.95 (3/10×3H, s, 4-Me), 3.4—3.8 (1H, m, CHP), 3.8—4.3 (4H, m, OEt), 4.83 (1H, m, OH), 5.1—5.5 (1H, m, CHOH), 5.94 (7/10H, d, J_{H-P}=3.0 Hz, 3-H), 6.26 (3/10H, d, J_{H-P}=3.0 Hz, 3-H), 6.96 (1H, m, 5-H), and 7.20 (5H, s, Ph).

7c: (a 4 : 1 mixture of two diastereomers): Colorless viscous liquid; IR (neat) 3400, 2970, 1615, 1230, 1025, and 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.87 (3H, m, *n*-Pr), 1.1—1.7 (10H, m, OEt and *n*-Pr), 2.02 (3H, s, 4-Me), 3.1—3.5 (1H, m, CHP), 3.8—4.4 (6H, m, OEt and CHOH), 6.14 (4/5H, d, J=3.0 Hz, 3-H), 6.34 (1H, d, J=3.0 Hz, 3-H), and 7.13 (1H, m, 5-H); MS *m/z* (rel intensity, %) 232 (M^+−PrCHO, base peak), 204 (22), 176 (33), and 95 (30).

7d: Colorless viscous liquid; IR (neat) 3440, 2980, 1610, 1225, 1025, and 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.16, 1.31 (each 3H, t, J=7.0 Hz, OEt), 1.4—2.1 (8H, m, CH_2), 1.90 (3H, s, 4-Me), 3.39 (1H, d, J_{H-P}=24.0 Hz, CHP), 3.6—4.3 (4H, m, OEt), 6.30 (1H, d, J_{H-P}=3.0 Hz, 3-H), and 7.10 (1H, br s,

5-H); MS *m/z* (rel intensity, %) 316 (M^+, 7), 232 (M^+—cyclopentanone, base peak), and 95 (23).

7e: Colorless viscous liquid; IR (neat) 3440, 2940, 1630, 1225, 1025, and 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.16, 1.29 (each 6H, t, J=7.0 Hz, OEt), 1.0—1.9 (10H, m, CH_2), 1.99 (3H, d, J=1.2 Hz, 4-Me), 3.40 (1H, d, $J_{H\text{-}P}$=24.0 Hz, CHP), 3.6—4.3 (5H, m, OEt), 6.27 (1H, d, $J_{H\text{-}P}$=3.0 Hz, 3-H), and 7.22 (1H, q, J=1.2 Hz, 5-H); MS *m/z* (rel intensity, %) 330 (M^+, 3), 232 (M^+—cyclohexanone), 159 (base peak), 129 (31), 126 (68), 117 (81), and 91 (73). HRMS Found: *m/z* 330.1592. Calcd for $C_{16}H_{27}O_5P$: M, 330.1595.

7f: Colorless viscous liquid; IR (neat) 3440, 2990, 1610, 1225, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.82, 0.90 (each 3H, t, J=7.5 Hz, Et), 1.14, 1.32 (each 3H, t, J=7.0 Hz, OEt), 1.5—1.9 (4H, m, Et), 2.00 (3H, s, 4-Me), 3.48 (1H, d, $J_{H\text{-}P}$=24.0 Hz, CHP), 3.6—4.3 (5H, m, OEt), 6.30 (1H, d, $J_{H\text{-}P}$=3.0 Hz, 3-H), and 7.12 (1H, m, 5-H); MS *m/z* (rel intensity, %) 318 (M^+, 1), 232 (M^+—3-pentanone, base peak), 176 (29), and 95 (32).

7g: (a 4 : 1 mixture of two diastereomers): Colorless viscous liquid; IR (neat) 3440, 2940, 1610, 1225, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.89 (3H, t, J=7.0 Hz, *n*-C_5H_{11}), 1.0—1.7 (17H, m, OEt, Me, and *n*-C_5H_{11}), 2.02 (3H, s, 4-Me), 3.40 (1/5H, d, $J_{H\text{-}P}$=24.0 Hz, CHP), 3.45 (4/5H, $J_{H\text{-}P}$=24.0 Hz, CHP), 3.7—4.3 (4H, m, OEt), 4.38 (1H, s, OH), 6.23 (4/5H, d, $J_{H\text{-}P}$=3.0 /Hz, 3-H), 6.28 (1/5H, d, $J_{H\text{-}P}$=3.0 Hz, 3-H), and 7.12 (1H, m, 5-H); MS *m/z* (rel intensity, %) 346 (M^+, 0.1) and 232 (M^+—2-heptanone, base peak). Found: C, 58.70; H, 8.98%. Calcd for $C_{17}H_{31}O_5P$: C, 58.94; H, 9.02%.

7h: (a 4 : 1 mixture of two diastereomers): Colorless viscous liquid; IR (neat) 3430, 3000, 1640, 1610, 1225, 1025, and 790 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.1—1.4 (9H, m, OEt and Me), 1.4—1.9 (2H, m, CH_2), 1.9—2.4 (2H, m, $CHCH_2$), 2.00 (3H, s, 4-Me), 3.42 (1/5×2H, d, $J_{H\text{-}P}$=24.0 Hz, CHP), 3.45 (4/5×2H, d, $J_{H\text{-}P}$=24.0 Hz, CHP), 3.7—4.3 (4H, m, OEt), 4.44 (1H, br s, OH), 4.8—5.1 (2H, m, $=CH_2$), 5.80 (1H, m, CH), 6.23 (4/5H, d, $J_{H\text{-}P}$=3.0 Hz 3-H), 6.28 (1/5H, d, $J_{H\text{-}P}$=3.0 Hz, 3-H), and 7.12 (1H, br s, 5-H); MS *m/z* (rel intensity, %) 232 (M^+—5-hexen-2-one, 15), 176 (25), 95 (26), 81 (20), 55 (22), and 43 (base peak).

Condensation of 5b with Butanal Leading to 8a. At −78 °C butyllithium (15% in hexane, 0.29 ml, 0.469 mmol) was added to a solution of **5b** (0.109 g, 0.469 mmol) in dry THF (3 ml). The mixture was stirred under nitrogen for 30 min. After butanal (0.068 g, 0.08 ml, 0.938 mmol) was added, the resulting mixture was stirred at −78 °C for 1 h, at −15 °C for 1 h, at 0 °C for 3 h, and at room temperature for 16 h. Saturated aqueous ammonium chloride (20 ml) was added and the extraction with diethyl ether (30 ml×3) followed. The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed over silica gel by using hexane to give **8a** (0.023 g, 33%). From the fraction with hexane-ethyl acetate (1 : 3 v/v) the unreacted **5b** (0.028 g, 26%) was recovered. **8a** (*E* : *Z*=98 : 2 by GLC): Colorless liquid; IR (neat) 2900, 1600, and 960 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.92 (3H, t, *n*-Pr), 1.2—1.7 (2H, m, *n*-Pr), 2.0—2.3 (2H, m, $=CHCH_2$), 2.25 (3H, s, 5-Me), and 5.8—6.3 (4H, m, 3-, 4-H, and CH=CH); MS *m/z* (rel intensity, %) 150 (M^+, 55), 122 (11), 121 (base peak), 91 (13), and 77 (14). Elemental analysis by HRMS was not attempted because of its easy polymerization.

Dehydration of Adducts 7b—h Leading to 8b—h. A mixture of adduct **7** (1 mmol) and cesium fluoride (0.578 g, 3.8 mmol) in wet DMF (2 ml containing water (0.07 ml)) was heated at 60 °C for 33—36 h. Diethyl ether (80 ml) was added, the ether solution was washed with water (50 ml×5), dried over magnesium sulfate, and evaporated in vacuo. The residue was chromatographed over silica gel with hexane to give **8** as rather unstable products. Further elution with the eluents shown below gave unreacted **7** and/or **5d** as a retro addition product.

8b: (*E* : *Z*=99 : 1 by GLC): Pale yellow prisms (hexane); mp 60—62 °C; IR (KBr) 1600 and 960 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.98 (3H, d, J=1.0 Hz, Me), 6.17 (1H, s, 3-H), 6.76 (1H, J=16.0 Hz, furylCH=), 6.91 (1H, s, 5-C), and 7.0—7.5 (6H, m, PhCH=); ^{13}C NMR ($CDCl_3$) δ=111.48 (d, 3-C), 116.89 (d, furylCH=), 122.13 (s, 4-C), 126.48, 127.01, 127.66, 128.83 (each d), 137.36 (s), 139.19 (d, 5-C), and 153.48 (s, 2-C); MS *m/z* (rel intensity, %) 184 (M^+, base peak), 155 (31), 141 (41), and 116 (25). Found: C, 84.18; H, 6.52%. Calcd for $C_{13}H_{12}O$: C, 84.75; H, 6.56%. The elution with hexane-ethyl acetate (1 : 2 v/v) afforded **5d** (20%).

8c: (*E* : *Z*=96:4 by GLC): Colorless liquid; IR (neat) 2940, 1600, and 960 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.92 (3H, t, J=7.0 Hz, *n*-Pr), 1.3—1.7 (2H, m, *n*-Pr), 1.96 (3H, s, 4-Me), 2.0—2.3 (2H, m, CH_2CH=), 6.06 (1H, d, J=15.5 Hz, furylCH=), 6.0—6.2 (1H, m, *n*-PrCH=), 6.10 (1H, s, 3-H), and 7.06 (1H, br s, 5-H); MS *m/z* (rel intensity, %) 150 (M^+, 19), 121 (28), 64 (21), 57 (29), 55 (27), and 43 (base peak). HRMS Found: *m/z* 150.1035. Calcd for $C_{10}H_{14}O$: M, 150.1044. The elution with hexane-ethyl acetate (1 : 2 v/v) gave a mixture of **7c** and **5d** (**7c**: 18%, **5d**: 4%).

8d: The reaction of **7d** (0.17 g, 0.537 mmol) with cesium fluoride (0.31 g, 2.041 mmol) in wet DMF (6.1 ml containing 0.04 ml of water) was heated at 60 °C for 30 h. Another portions of cesium fluoride (0.31 g, 2.041 mmol) and water (0.04 ml) were added and the heating was continued at 60 °C for 15 h and then at 80 °C for 5.5 h. A similar work-up gave **8d** (0.086 g, 78%). **8d**: Colorless liquid; IR (neat) 2960, 1660 and 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.4—2.0 (4H, m, CH_2), 2.00 (3H, s, 4-Me), 2.3—2.6 (4H, m, CH_2), 5.99 (1H, s, 3-H), 6.18 (1H, tt, J=2.1 and 2.1 Hz, CH), and 7.08 (1H, s, 5-H); MS *m/z* (rel intensity, %) 162 (M^+, base peak), 121 (49), 105 (20), 91 (36), and 77 (20). HRMS Found: *m/z* 162.1048. Calcd for $C_{11}H_{14}O$: M, 162.1044. The fraction eluted with hexane-ethyl acetate (1 : 2 v/v) gave **7d** (0.005 g, 3%) and then **5d** (0.008 g, 6%).

8e: Colorless liquid; IR (neat) 2930, 1655, and 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.4—1.8 (6H, m, CH_2), 1.99 (3H, d, J=1.2 Hz, 4-Me), 2.22 (2H, m, CH_2CH=), 2.58 (2H, m, CH_2), 5.89 (1H, s, CH=), 6.02 (1H, s, 3-H), and 7.06 (1H, t, J=1.2 Hz, 5-H); MS *m/z* (rel intensity, %) 176 (M^+, base peak), 108 (55), and 95 (21). HRMS Found: *m/z* 176.1186. Calcd for $C_{12}H_{16}O$: M, 176.1200. The fraction eluted with hexane-ethyl acetate (2 : 1 v/v) gave **7e** (5%).

8f: Colorless liquid; IR (neat) 2960, 1655, and 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.06 (6H, t, J=7.0 Hz, Et), 2.00 (3H, s, 4-Me), 2.18, 2.40 (each 2H, q, J=7.0 Hz, Et), 5.94 (1H, s, CH=), 6.04 (1H, s, 3-H), and 7.09 (1H, m, 5-H); MS *m/z* (rel intensity, %) 164 (M^+, base peak), 149 (22), 135 (91), 107 (26), 93 (22), and 91 (28). HRMS Found: *m/z* 164.1209. Calcd for $C_{11}H_{16}O$: M, 164.1200. The fraction eluted with hexane-ethyl acetate (1 : 1 v/v) provided **7f** (3%) and with eluent of 1 : 2 v/v gave **5d** (8%).

8g: (*E* : *Z*=80 : 20 by GLC): Colorless liquid; IR (neat) 2940, 1655, and 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.87 (3H, t, J=7.0

Hz, n-C_5H_{11}), 1.1—1.6 (6H, m, n-C_5H_{11}), 1.83 (20/100×3H, d, 1.0 Hz, =CMe, *Z*), 1.90 (80/100×3H, d, *J*=1.0 Hz, =CMe, *E*), 1.95 (3H, s, 4-Me), 2.0—2.5 (2H, m, =CCH_2), 5.98 (2H, s, 3-H and =CH), and 7.03 (s, 5-H); ^{13}C NMR ($CDCl_3$) δ=9.76 (q, 4-Me, *Z*), 9.81 (q, 4-Me, *E*), 14.07 (q, n-C_5H_{11}), 18.46 (q, =CMe, *E*), 22.63 (t, CH_2), 24.66 (q, =CMe, *Z*), 27.54 (t, CH_2, *Z*), 27.73 (t, CH_2, *E*), 31.53 (t, CH_2, *E*), 32.08 (t, CH_2, *Z*), 33.62 (t, =CCH_2, *Z*), 40.79 (t, =CCH_2, *E*), 109.76 (d, 3-C, *Z*), 110.10 (d, 3-C, *E*), 114.16 (d, =CH, *E*), 114.41 (d, =CH, *Z*), 121.18 (s, 4-C, *Z*), 121.29 (s, 4-C, *E*), 137.19 (d, 5-C, *Z*), 137.25 (d, 5-C, *E*), 138.66 (s, =C, *E*), 139.39 (s, =C, *Z*), 153.50 (s, 2-C, *Z*), and 153.85 (s, 2-C, *E*); MS *m/z* (rel intensity, %) 192 (M^+, 84), 135 (base peak), 122 (20), 107 (34), and 91 (38). HRMS Found: *m/z* 192.1528. Calcd for $C_{13}H_{20}O$: M, 192.1513. The fraction eluted with hexane-ethyl acetate (1 : 1 v/v) gave **7g** (0.019 g, 6%) and with eluent of 1 : 2 v/v afforded **5d** (0.01 g, 10%).

8h: (*E* : *Z*=82 : 18 by GLC): Colorless liquid; IR (neat) 2940, 1660, 1640, and 1600 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.87 (18/100×3H, d, *J*=1.2 Hz, =CMe), 1.94 (82/100×3H, d, *J*=1.2 Hz, =CMe), 2.00 (3H, *J*=1.2 Hz, 4-Me), 2.1—2.6 (4H, m, CH_2), 4.9—5.2 (2H, m, =CH_2), 5.6—6.0 (1H, m, CH=), 6.01 (1H, s, 3-H), and 7.08 (1H, t, *J*=1.2 Hz, 5-H); ^{13}C NMR ($CDCl_3$) δ=9.76 (q, 4-Me), 18.50 (q, =CMe, *E*), 24.62 (q, =CMe, *Z*), 31.98 (t, CH_2, *Z*), 32.32 (t, CH_2, *E*), 32.94 (t, =CCH_2, *Z*), 40.16 (t, =CCH_2, *E*), 109.96 (d, 3-C, *Z*), 110.29 (d, 3-C, *E*), 114.76 (t, =CH_2), 121.28 (s, 4-C), 137.32 (d, CH=), 137.49 (d, 5-C), 138.17 (s, =CMe, *E*), 138.51 (s, =CMe, *Z*), 153.26 (s, 2-C, *Z*), and 153.62 (s, 2-C, *E*); MS *m/z* (rel intensity, %) 176 (M^+, 38), 135 (base peak), 107 (46), 91 (49), and 79 (25). HRMS Found: *m/z* 176.1197. Calcd for $C_{12}H_{11}O$: M, 176.1200. The fraction eluted with hexane-ethyl acetate (1 : 1 v/v) gave **7h** (0.008 g, 4%) and with eluent of 1 : 2 v/v afforded **5d** (0.019 g, 12%).

4-Methyl-2-(1-oxohexyl)furan (9a): To a solution of **5i** (0.265 g, 0.876 mmol) in dry THF (4 ml) was added butyllithium (15% in hexane, 0.55 ml, 0.876 mmol) at −78 °C and stirred for 1 h. After dry oxygen gas was bubbled at −100 °C for 15 min, aqueous THF (50%, 20 ml) was slowly added. The products were extracted with diethyl ether (30 ml×3). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed over silica gel with hexane-ethyl acetate (10 : 1 v/v) to give **9a** (0.047 g, 30%): Colorless liquid; IR (neat) 2930, 1675, and 1600 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.90 (3H, t, *J*=6.0 Hz, n-C_5H_{11}), 1.2—2.0 (6H, m, n-C_5H_{11}), 2.08 (3H, s. 4-Me), 2.77 (2H, t, *J*=6.0 Hz, $COCH_2$), 7.03 (1H, s, 3-H), and 7.33 (1H, t, *J*=1.0 Hz, 2-H); MS *m/z* (rel intensity, %) 180 (M^+, 9), 124 (base peak), 110 (63), 53 (22), 43 (24), and 41 (30). Found: C, 73.38; H, 8.94%. Calcd for $C_{11}H_{16}O$: C, 73.30; H, 8.95%.

4-Methyl-2-(1-oxo-2-phenylethyl)furan (9b): Dry oxygen gas was bubbled at −78 °C for 1 h through the anion solution generated by a similar method using **5j** (0.21 g, 0.65 mmol) and butyllithium (15% in hexane, 0.45 ml, 0.65 mmol) in dry THF (3 m]). Usual hydrolytic work-up and silica-gel column chromatography with hexane-ethyl acetate (5 : 1 v/v) afforded **9b** (0.026 g, 20%): Colorless needles (hexane); mp 60.5—61 °C; IR (KBr) 3100, 1650, and 1600 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=2.04 (3H, dd, *J*=1.0 and 0.5 Hz, Me), 3.04 (2H, s, CH_2), 7.03 (1H, t, *J*=0.5 Hz, 3-H), 7.26 (5H, br s, Ph), and 7.32 (1H, t, *J*=1.0 Hz, 5-H); MS *m/z* (rel intensity, %) 200 (M^+, 9), 110 (base peak), 91 (55), and 65 (44). Found: C, 77.79; H, 5.86%. Calcd for $C_{13}H_{12}O_2$: C, 77.98; H, 6.04%.

Hydrolysis of 2-(1-Phosphorylalkyl)furans 5b, c and 5g Leading to 2,5-Dioxoalkylphosphonates 10a—c. A furan **5** (1 mmol) in aqueous acetic acid (67%, 2—3 ml) containing a catalytic amount of concd sulfuric acid was heated at 120 °C for 5 h. The reaction mixture was diluted with water (40 ml), neutralized with saturated aqueous sodium hydrogencarbonate, and then extracted with ethyl acetate (50 ml×3). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed over silica gel to give **10** (**10a**: from ethyl acetate, 62%. **10b**: from ethyl acetate, 52%. **10c**: from hexane-ethyl acetate (3 : 2 v/v), 53%).

10a: Pale yellow liquid; IR (neat) 1710, 1250, 1020, and 800 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.33 (6H, t, *J*=7.0 Hz, OEt), 2.17 (3H, s, Me), 2.6—3.0 (4H, m, CH_2), 3.12 (2H, d, $J_{H\text{-}P}$=22.5 Hz, PCH_2), and 4.13 (4H, dq, $J_{H\text{-}P}$=7.8 and *J*=7.0 Hz, OEt); MS *m/z* (rel intensity, %) 250 (M^+, 7), 232 (34), 208 (31), 207 (70), 179 (98), 153 (56), 152 (76), 125 (53), 123 (52), 109 (42), 97 (28), 95 (51), 81 (34), and 43 (base peak). HRMS Found: *m/z* 250.0969. Calcd for $C_{10}H_{19}O_5P$: M, 250.0969.

10b: Pale yellow liquid; IR (neat) 1710, 1250, 1020, and 815 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.05 (3H, t, *J*=7.0 Hz, Et), 1.33 (6H, t, *J*=7.0 Hz, OEt), 2.47 (2H, q, *J*=7.0 Hz, Et), 2.6—3.0 (4H, m, CH_2), 3.12 (2H, d, $J_{H\text{-}P}$=22.5 Hz, PCH_2), and 4.13 (4H, dq, $J_{H\text{-}P}$=8.0 and *J*=7.0 Hz, OEt); ^{13}C NMR ($CDCl_3$) δ=7.77 (q, Et), 16.29 (dq, $J_{C\text{-}P}$=5.9 Hz, OEt), 35.77, 37.65 (each t, $COCH_2$), 42.50 (dt, $J_{C\text{-}P}$=128.0 Hz, PCH_2), 62.65 (dt, $J_{C\text{-}P}$=5.9 Hz, OEt), 201.01 (d, $J_{C\text{-}P}$=5.9 Hz, CO), and 209.72 (s, CO); MS *m/z* (rel intensity, %) 264 (M^+, 19), 246 (36), 235 (41), 208 (44), 207 (95), 179 (base peak), 153 (46), 152 (60), 125 (30), 123 (30), and 109 (32). HRMS Found: *m/z* 264.1116. Calcd for $C_{11}H_{21}O_5P$: M, 264.1125.

10c: Pale yellow liquid; IR (neat) 1710, 1250, 1025, and 790 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.87 (3H, t, *J*=6.0 Hz, n-C_8H_{17}), 1.05 (3H, t, *J*=7.0 Hz, Et), 1.1—1.4 (12H, m, n-C_8H_{17}), 1.32 (6H, t, *J*=7.0 Hz, OEt), 1.5—2.1 (2H, m, n-C_8H_{17}), 2.49 (2H, q, *J*=7.0 Hz, Et), 2.5—3.4 (5H, m, PCH and $COCH_2$), and 4.11 (4H, dq, $J_{H\text{-}P}$=8.0 and *J*=7.0 Hz, OEt); ^{13}C NMR ($CDCl_3$) δ=7.88 (q, Et), 14.12 (q, n-C_8H_{17}). 16.41 (dq, $J_{C\text{-}P}$=5.9 Hz, OEt), 22.71 (t, n-C_8H_{17}), 26.68 (dt, $J_{C\text{-}P}$=4.4 Hz, n-C_8H_{17}), 28.41 (dt, $J_{C\text{-}P}$=14.7 Hz, n-C_8H_{17}), 29.24, 29.41, 31.88 (each t, n-C_8H_{17}), 35.71, 35.94, 38.06 (each t, CH_2CO), 52.97 (dd, $J_{C\text{-}P}$=125.0 Hz, PCH), 62.56 (dt, $J_{C\text{-}P}$=4.4 Hz, OEt), 62.77 (dt, $J_{C\text{-}P}$=5.90 Hz, OEt), 205.04 (d, $J_{C\text{-}P}$=4.4 Hz, CO), and 209.71 (s, CO); MS *m/z* (rel intensity, %) 376 (M^+, 15), 347 (28), 319 (48), 291 (29), 264 (base peak), 263 (36), 221 (26), 207 (41), 179 (27), 165 (48), 153 (46), and 110 (26). HRMS Found: *m/z* 376.2365. Calcd for $C_{19}H_{37}O_5P$: M, 376.2377.

3-Ethyl-2-octyl-2-cyclopenten-1-one (11). A mixture of lithium bromide (0.029 g, 0.33 mmol) and **10c** (0.083 g, 0.22 mmol) in dry THF (3.5 ml) was stirred at room temperature for 10 min. After cooled to 0 °C triethylamine (0.027 g, 0.04 ml, 0.246 mmol) was added. The resulting mixture was stirred for 1.5 h at room temperature, heated under reflux for 24 h, diluted with water (20 ml), and then extracted with diethyl ether (30 ml×3). The combined extracts were dried (magnesium sulfate) and evaporated in vacuo. The residue was chromatographed over silica gel by using hexane-ethyl acetate (3 : 1 v/v) as an eluent to give **11** (0.015 g, 31%). The starting **10c** (0.01 g, 12%) was recovered from a fraction eluted with hexane-ethyl acetate (1 : 1 v/v): Pale yellow liquid; IR (neat) 1700 and 1640 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.86 (3H, t, *J*=6.0 Hz, n-C_8H_{17}), 1.12 (3H, t, *J*=7.5 Hz, Et), 1.0—1.5 (12H, m, n-C_8H_{17}), and 2.0—2.6 (8H, m, CH_2C=, 4- and

5-H); MS *m/z* (rel intensity, %) 222 (M^+, 16), 193 (base peak), 124 (60), 123 (24), and 79 (23). HRMS Found: *m/z* 222.1982. Calcd for $C_{15}H_{26}O$: M, 222.1982.

Synthesis of Furanosesquiterpene 12. To a solution of **5d** (0.188 g, 0.81 mmol) in dry THF (2 ml) was added butyllithum (15% in hexane, 0.51 ml, 0.81 mmol) at −78 °C under nitrogen. After the mixture was stirred for 1 h, **13** (*E*:*Z*=75:25, 0.168 g, 1.215 mmol) was added and the stirring was continued for 30 min. The mixture was treated with saturated ammonium chloride solution (20 ml) and extracted with dichloromethane (30 ml×3). The combined extracts were dried over magnesium sulfate and evaporated in vacuo. The residue was chromatographed over silica gel with hexane-ethyl acetate (3:1 v/v) to give **14** (0.237 g, 79%). The fraction eluted with hexane-ethyl acetate (1:1 v/v) afforded the starting **5d** (0.022 g, 12%). **14** (a mixture of diastereomers, *E*:*Z*=3:1 by ^{1}H NMR): Colorless viscous liquid; IR (neat) 3440, 3000, 1640, 1610, 1225, and 1025 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.2—1.8 (14H, m, OEt, CH_2, MeC(OH), and MeCH=), 2.01 (3H, 4-Me), 2.1—2.3 (2H, m, CH_2CH), 3.41 (1/4H, d, $J_{H\text{-}P}$=23.8 Hz, PCH, *Z*), 3.47 (3/4H, d, $J_{H\text{-}P}$=23.5 Hz, PCH, *E*), 3.8—4.3 (4H, m, OEt), 4.46 (1H, s, OH), 4.9—5.4 (2H, m, CH_2), 6.23, 6.28 (1H, each d, $J_{H\text{-}P}$=3.3 Hz, 3-H), 6.33 (3/4H, dd, *J*=17.2 and 10.6 Hz, CH=, *E*), 6.7—6.8 (1/4H, m, CH=, *Z*), and 7.13 (1H, s, 5-H); MS *m/z* (rel intensity, %) 370 (M^+, 3), 232 (base peak), and 95 (23). HRMS Found: *m/z* 370.1906. Calcd for $C_{19}H_{31}O_5P$: M, 370.1907. A mixture of **14** (0.21 g, 0.567 mmol), cesium fluoride (0.327 g, 2.155 mmol), and water (0.04 ml, 2.155 mmol) in DMF (6.5 ml) was heated at 60 °C for 38 h. Diethyl ether (100 ml) was added to the mixture, the organic layer was washed with water (100 ml×4), dried over magnesium sulfate, and evaporated in vacuo. The residue was chromatographed over silica gel by using hexane as an eluent to give **12** (0.074 g, 53%). The fraction eluted with hexane-ethyl acetate (1:2 v/v) gave **5d** (0.017 g, 13%). **12** (a 59:20:15:6-mixture of **12a**:**12b**:**12c**:**12d** by GLC): Colorless liquid; IR (neat) 2940, 1640, and 1610 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.56, 1.75, 1.81, 1.87, 1.96, 2.00, 2.02 (9H, each s, Me), 2.2—2.4 (4H, m, CH_2), 4.9—5.2 (2H, m, $=CH_2$), 5.4—5.6 (1H, m, 5′-H), 6.04 (2H, m, 3- and 1′-H), 6.36 (59/100H, dd, *J*=17.1 and 10.8 Hz, 7′-H of **12a**), 6.37 (15/100H, dd, *J*=17.1 and 10.8 Hz, 7′-H of **12c**), 6.78 (20/100H, dd, *J*=17.1 and 10.8 Hz, 7′-H of **12b**), 6.80 (6/100H, dd, *J*=17.1 and 10.8 Hz, 7′-H of **12d**), and 7.10 (1H, s, 5-H); ^{13}C NMR ($CDCl_3$) δ=9.76 (q, 4-Me), 11.63 (q, 6′-Me of **12c**), 11.68 (q, 6′-Me of **12a**), 18.52 (q, 2′-Me of **12a**), 19.74 (q, 2′-Me of **12b**, 6′-Me of **12b**, and 6′-Me of **12d**), 24.71 (q, 2′-Me of **12c**), 25.74 (q, 2′-Me of **12d**), 25.85 (t, 4′-C, **12d**), 26.00 (t, 4′-C of **12b**), 26.75 (t, 4′-C of **12c**), 26.91 (t, 4′-C of **12a**), 33.38 (t, 3′-C of **12c**), 33.78 (t, 3′-C of **12d**), 40.36 (t, 3′-C of **12a**), 40.75 (t, 3′-C of **12b**), 110.05 (d, 3-C of **12d**), 110.08 (d, 3-C of **12c**), 110.36 (d, 3-C of **12a** and 3-C of **12b**), 110.64 (t, 8′-C of **12a**), 110.87 (t, 8′-C of **12c**), 113.42 (t, 8′-C of **12d**), 113.57 (t, 8′-C of **12b**), 114.57 (d, 1′-C of **12a** and 1′-C of **12b**), 114.91 (d, 1′-C of **12d**), 115.09 (d, 1′-C of **12c**), 121.19 (s, 4-C of **12c** and 4-C of **12d**), 121.29 (s, 4-C of **12a** and 4-C of **12b**), 130.15 (d, 5′-C of **12b**), 130.58 (d, 5′-C of **12d**), 132.13 (d, 5′-C of **12a**), 132.65 (d, 5′-C of **12c**), 133.63 (6′- and 7′-C of **12b**), 133.74 (6′- and 7′-C of **12d**), 134.31 (s, 6′-C of **12c**), 134.38 (s, 6′-C of **12a**), 137.00, 137.46, 137.52, 137.85, 138.11, 141.49 (d, 7′-C of **12a**), 141.56 (d, 7′-C of **12c**), 153.26 (s, 2-C of **12c** and 2-C of **12d**), and 153.59 (s, 2-C of **12a** and 2-C of **12b**); MS *m/z* (rel intensity, %) 216 (M^+, 27), 135 (base peak), 107 (38), 91 (31), 78 (15), and 41 (12). HRMS Found: *m/z* 216.1515. Calcd for $C_{15}H_{20}O$: M, 216.1513.

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