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Allylic Rearrangement of Cyanophosphate. II.[1] Synthesis of β-Cyano-α,β-unsaturated Ketones

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Boron trifluoride-catalyzed allylic rearrangement of the cyanophosphates of α,β-unsaturated ketones (**1a—d**, **7** and **14**) was found to give the allylic phosphates (**3a—d**, **9** and **16**), which were successfully converted to β-cyano-α,β-unsaturated ketones (**6a—d**, **13** and **20**) by acid hydrolysis (0.5 N HCl) followed by manganese dioxide oxidation of the resulting allylic alcohols (**5a—d**, **11**, **12** and **17**). The stereochemical features of the allylic phosphates (**9** and **16**) are discussed.

Keywords——α,β-unsaturated ketone; diethyl phosphorocyanidate; cyanophosphate; allylic rearrangement; boron trifluoride etherate; manganese dioxide; β-cyano-α,β-unsaturated ketone

The [2.3]sigmatropic rearrangement of allylic sulfoxides[3] and the palladium(II)-catalyzed [3.3]sigmatropic rearrangement of allylic acetates[4] are important for the introduction of an oxygen function at the β-position of allylic sulfoxides or acetates. Recent studies aimed at synthetic utilization of palladium-catalyzed rearrangement of α-cyanoallylic acetates[5] or α-methoxycarbonylallylic phosphate[6] have been reported. We recently reported that boron trifluoride (BF_3)-catalyzed rearrangement of α-cyanoallylic phosphates is useful for the introduction of an oxygen function at the β-position of α,β-unsaturated ketones.[1,7]

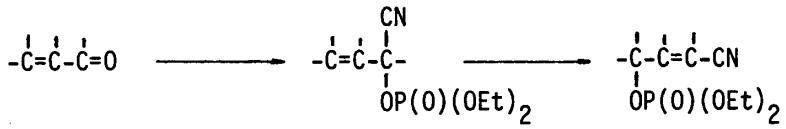
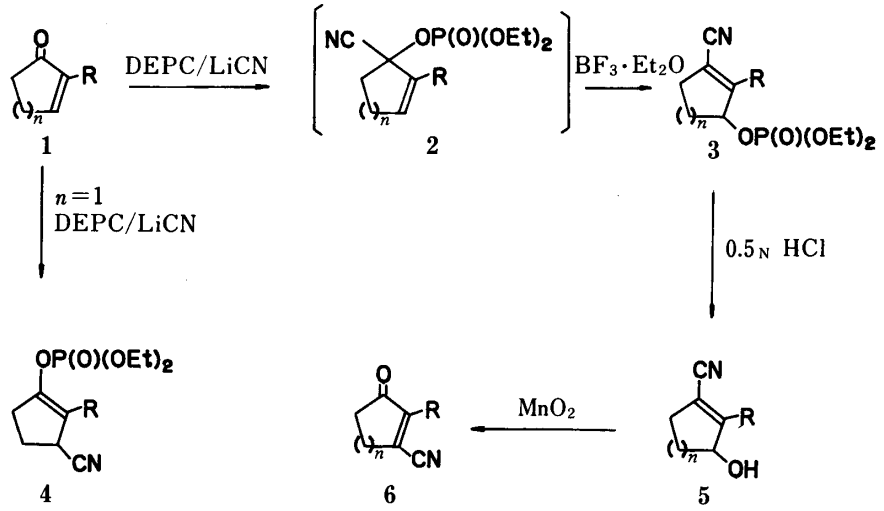


Chart 1

Recently Nudelman and Keinan reported an efficient synthesis of 4-oxo-2-alkenenitriles, enedicarbonyl synthons, from 2-alkenals *via* a sequence of reactions: acetoxycyanation, palladium(0)-catalyzed isomerization, basic hydrolysis (CH_3ONa in CH_3OH), and oxidation (oxalyl chloride–dimethyl sulfoxide).[5b] From this point of view, we would like to describe here a facile synthesis of cyclic β-cyano-α,β-unsaturated ketones (cyclic 4-oxo-2-alkenenitriles) (**6a—d**, **13** and **20**) from enones (**1a—d**, **7** and **14**) by cyanophosphorylation, BF_3-catalyzed allylic rearrangement, and acid hydrolysis, followed by oxidation with manganese dioxide of the resulting allylic alcohols (**5a—d**, **11**, **12** and **17**). The products were obtained in moderate to high yields. In general, cyanophosphorylation of enones (1 mmol) was carried out in tetrahydrofuran (THF) at room temperature using diethyl phosphorocyanidate (DEPC) (3 mmol) and lithium cyanide (LiCN) (3 mmol) under nitrogen as described in a previous communication.[7]

Treatment of 2-methyl-2-cyclohexen-1-one (**1a**) with DEPC/LiCN in THF afforded the crude cyanophosphate (**2a**), whose proton nuclear magnetic resonance (^{1}H-NMR) spectrum

showed a vinyl proton at δ 5.80 as a broad singlet. Without purification, the crude material in benzene solution was stirred with a catalytic amount of BF_3 etherate (0.1 eq) at room temperature for 2 h to give 1-cyano-3-diethylphosphonooxy-1-cyclohexene (**3a**) in 80% overall yield. The use of an equimolar amount of BF_3 etherate resulted in a lower yield of **3a**. When a solution of **2a** in benzene was refluxed for 20 h without addition of BF_3 etherate, **3a** was obtained in only 48% yield, thus showing the effectiveness of BF_3 etherate as a catalyst for the allylic rearrangement of cyanophosphate (**2a**). The ^{1}H-NMR spectrum of **3a** exhibited a broad singlet at δ 4.80 due to the C-3 proton. The infrared (IR) spectrum of **3a** showed a strong nitrile absorption at 2220 cm^{-1}, which was not usually observed in **2a**. 2-Cyclohexen-1-

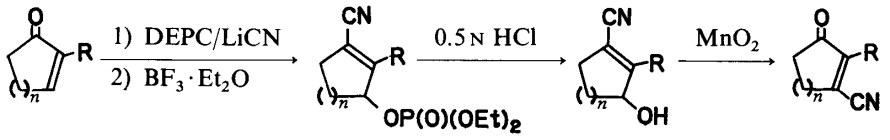


a : n=2, R=Me; **c** : n=1, R=Me
b : n=2, R=H ; **d** : n=1, R=H

Chart 2

one (**1b**) was analogously converted into the cyanophosphate (**2b**) which underwent a BF_3 etherate-catalyzed allylic rearrangement to **3b** in 81% overall yield. Contrary to the cases of the six-membered enones, 2-cyclopenten-1-one (**1d**) has been found to react with DEPC/LiCN at room temperature to afford the enol phosphate (**4d**) in 74% yield. Structural assignment of **4d** was readily performed by acid hydrolysis (0.5 N HCl) to give 3-cyanocyclopentanone.[8] On the other hand, reaction of **1d** with DEPC/LiCN at lower temperature (−17 °C) in THF was found to give a mixture of the cyanophosphate (**2d**) as a major product and **4d** as a minor product as judged from the ^{1}H-NMR spectrum. Without purification, the mixture was treated with BF_3 etherate (0.1 eq) to afford **3d** in 64% overall yield and **4d** in 11% yield after column chromatography on silica gel (SiO_2). Similarly, reaction of 2-methyl-2-cyclopenten-1-one (**1c**) with DEPC/LiCN at room temperature (or −17 °C) followed by treatment with BF_3 etherate afforded the allylic phosphate (**3c**) in 27% yield (51%) and the enol phosphate (**4c**) in 40% (6%) yield, respectively. Hydrolysis of **3a**—**3d**, thus obtained, with 0.5 N hydrochloric acid under reflux gave the allylic alcohols (**5a**—**5d**), which were then oxidized with manganese dioxide (MnO_2) in chloroform ($CHCl_3$) to give β-cyano-α,β-unsaturated ketones (**6a**—**6d**). Yields of allylic phosphates, allylic alcohols and β-cyanoenones are summarized in the table. Compound **6a** is an important intermediate for the preparation of homosarkomycin and has been synthesized from **1a** *via* a sequence of reactions, hydrocyanation, chlorination, and dehydrochlorination, in 17% overall yield[9] (in our case 75% overall yield was obtained). In connection with stereochemical aspects of the cyanophosphorylation and allylic rearrangement, 4-*tert*-butyl-2-cyclohexen-1-one (**7**)[10] was treated with DEPC/LiCN to give the cyanophosphate (**8**), which was then subjected to allylic rearrangement by treatment with BF_3

TABLE I. Yields (%) of Allylic Phospates (**3**), Allylic Alcohols (**5**), and β-Cyanoenones (**6**)



Compounds No.			
[Yields (%)]	**3a**	**5a**	**6a**
	[80]	[100]	[93]
	3b	**5b**	**6b**
	[81]	[98]	[93]
	3c	**5c**	**6c**
	[51]	[78]	[84]
	3d	**5d**	**6d**
	[64]	[70]	[77]

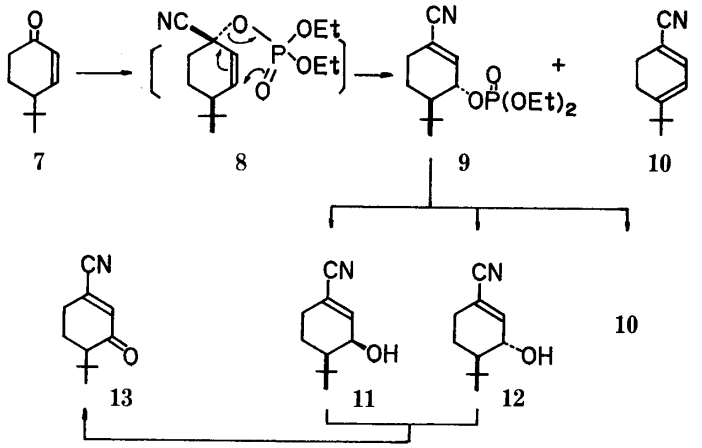


Chart 3

etherate to give **9** in 51% yield, accompanied with the formation of the diene nitrile (**10**) in 38% yield. The stereochemistry of **9**, having a quasi-equatorial orientation of the diethyl phosphonooxy group, was assigned on the basis of the coupling constant (7 Hz) of the C-3 proton which appeared in the ^{1}H-NMR spectrum as a broad triplet at δ 4.93 coupled with the C-4 proton and phosphorus atom when the C-2 proton was irradiated. Therefore, it is assumed that the product **9** was formed *via* [3.3]sigmatropic rearrangement of the cyanophosphate (**8**) in which the bulky diethylphosphonooxy group is in a quasi-equatorial orientation. The structure of **10** was determined on the basis of ^{1}H-NMR spectral evidence [δ 5.84 and 6.67 (each 1H, each d, J=7 Hz) due to two vinyl protons] and further by dehydrogenation (10% palladium–carbon in toluene) of **10** to give 4-*tert*-butylbenzonitrile.[11] Acid hydrolysis (0.5 N HCl in EtOH) of **9** gave a mixture of two alcohols (**11** and **12**) in the ratio of 1 : 1 in 41% yield and **10** in 24% yield. The two alcohols (**11** and **12**) could be partially separated by SiO_2 column chromatography (**11** as an oil and **12** as crystals). Assignments of the *cis*- and *trans*-stereochemistry of the C_3- and C_4-hydrogens in **11** and **12** were made on the basis of their coupling constants ($J_{3,4}$=3.5 Hz in **11** and $J_{3,4}$=8 Hz in **12**) in the ^{1}H-NMR spectra by means of the irradiation technique. Oxidation of a mixture of **11** and **12** with MnO_2 in $CHCl_3$ gave the enone (**13**) in 75% yield.

Finally, as an extension of the model experiments, the reaction of 1-acetyl-1-cyclohexene (**14**) with DEPC/LiCN followed by treatment with BF_3 etherate was examined. Under the procedure described above **14** gave the conjugate phosphate (**16**), which was found to be a

single product (by thin layer chromatography), in 78% yield. However, the ^{1}H-NMR spectrum of **16** showed two broad signals due to the C-1 proton at δ 5.32 and 5.42 in the ratio of 1 : 9. By means of the irradiation technique, it was found that the C-1 proton couples with the phosphorus atom and C-3 methylene protons with coupling constants of 7.2 and 3.5 Hz, respectively. Therefore, the phosphate **16** is a mixture of *Z*- and *E*-isomers. This mixture was hydrolyzed with 0.5 N HCl under reflux to give three products after column chromatography on SiO_2. The major product (23%) was assigned as the diene nitrile (**19**) [MS *m/e*: 133 (M^+)], whose ^{1}H-NMR spectrum showed the presence of *Z*- and *E*-isomers in the ratio of 7 : 3. The C-2 proton of the *Z*-isomer resonates at lower field [δ 6.65 (br d, J = 10.4 Hz)] than that of the *E*-isomer [δ 6.41 (br d, J = 9.8 Hz)] due to the anisotropic effect of the nitrile group located on the same side. The second product (19%) was assigned the structure **18** on the basis of the IR spectroscopic evidence (a strong carbonyl absorption at 1750 cm^{-1}, and no absorption bands due to a hydroxyl or nitrile group). The structure of the third product (19%) was identified as 2-(1-cyanoethylidene)-1-cyclohexanol (**17**). The stereochemical assignment was made on the basis of spectroscopic evidence. The ^{1}H-NMR spectrum showed the C-1 proton signal as a triplet (J = 3.3 Hz) at δ 4.75, indicating the hydroxyl group to be in a quasi-equatorial orientation. Irradiation of the methyl signal caused at 10% increase in the integrated intensity of the C-1 proton signal, without affecting on the C-3 methylene proton signals, based on measurement of the intramolecular nuclear Overhauser effect. These findings indicate that **17** is the *E*-isomer. This was phosphorylated with diethyl phosphorochloridate in the presence of lithium diisopropylamine (LDA) at −78 °C to give **16** as a single product in 76% yield; the C-1 proton signal of **16** at δ 5.32 in the ^{1}H-NMR spectrum was identical with that of the minor component of conjugated phosphate (**16**) obtained from **15**. Thus, it was concluded that the major component of **16** is the *Z*-isomer and the minor one is the *E*-isomer. Compound **17** or the *E*-isomer of **19** is presumably formed *via* isomerization of *Z*-**16** during hydrolysis. Oxidation of **17** with MnO_2 in $CHCl_3$ gave **20** in 68% yield.

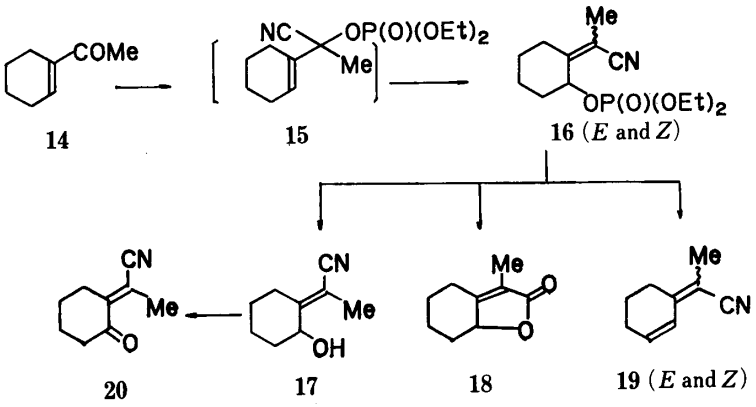


Chart 4

In conclusion, α,β-unsaturated ketones are cyanophosphorylated with DEPC/LiCN in THF, and subsequent reaction with BF_3 etherate gives the allylic phosphates. These are converted to β-cyanoenones by acid hydrolysis followed by MnO_2 oxidation of the resulting allylic alcohols.

Experimental

Melting points were taken on a Yanagimoto micromelting point apparatus and are uncorrected. The IR spectra were recorded neat with a Shimadzu IR 435 spectrophotometer unless otherwise noted. The ^{1}H-NMR spectra were recorded in $CDCl_3$ solution on a Varian XL-300 spectrometer. Chemical shifts are reported in parts per million (ppm) on the δ scale relative to tetramethylsilane as an internal standard. Mass spectra (MS) were recorded on a

Hitachi M-80 instrument.

General Procedure for Preparation of Allylic Phosphates——A mixture of an α,β-unsaturated ketone (1 mmol), DEPC (3 mmol) and LiCN (3 mmol) in THF (10 ml) was stirred at room temperature for 5 min (cyanophosphorylations of **1c** and **1d** were carried out at −17 °C for 1 h). After removal of the THF by evaporation, the residue was dissolved in water (10 ml) and benzene–ethyl acetate (EtOAc) (1 : 1, 50 ml). The organic layer was separated, and washed with water (10 ml × 2) and saturated NaCl solution (10 ml). Drying over Na_2SO_4 followed by evaporation gave a brown oil, which was stirred with BF_3 etherate (0.1 mmol) in benzene (20 ml) at room temperature for 2 h under N_2. After the addition of benzene (50 ml) and water (10 ml), the organic layer was separated, and washed with water (10 ml × 2) and saturated NaCl solution (10 ml). Drying over Na_2SO_4 followed by concentration gave the crude allylic phosphates, which were purified by SiO_2 column chromatography eluted with benzene–EtOAc (10 : 1). The allylic phosphates usually exhibited strong absorption bands at 1260—1270 and 1060—960 cm^{-1} in the IR spectra due to $-P(O)(OCH_2CH_3)_2$. The ^1H-NMR spectra of the allylic phosphates showed multiplets at δ 1.30—1.42 (6H, OCH_2CH_3) and 4.05—4.20 (4H, OCH_2CH_3).

1-Cyano-3-diethylphosphonooxy-2-methyl-1-cyclohexene (**3a**): This was prepared by the general procedure from **1a** *via* cyanophosphate (**2a**) as a colorless oil of bp_1 125—127 °C (Kugelrohr). IR ν_{max} cm^{-1}: 2220 (CN), 1640 (C=C). ^1H-NMR δ: 2.12 (3H, br s, CH_3), 4.80 (1H, br s, C_3-H). MS *m/e*: 273 (M^+). *Anal.* Calcd for $C_{12}H_{20}NO_4P$: C, 52.74; H, 7.37; N, 5.13. Found; C, 52.59; H, 7.36; N, 5.22.

1-Cyano-3-diethylphosphonooxy-1-cyclohexene (**3b**): This was prepared by the general procedure from **1b** *via* cyanophosphate (**2b**) as a colorless oil of bp_1 120—126 °C (Kugelrohr). IR ν_{max} cm^{-1}: 2220 (CN), 1630 (C=C). ^1H-NMR δ: 4.96 (1H, br s, C_3-H), 6.65 (1H, br s, C_2-H). MS *m/e*: 259 (M^+). *Anal.* Calcd for $C_{11}H_{18}NO_4P$: C, 50.96; H, 7.00; N, 5.40. Found: C, 51.09; H, 7.11; N, 5.46.

1-Cyano-3-diethylphosphonooxy-2-methyl-1-cyclopentene (**3c**): The crude extract, obtained by the general procedure *via* cyanophosphorylation of **1c** (481 mg, 5 mmol) at −17 °C, was purified by SiO_2 column chromatography. The first fraction of the benzene–EtOAc (20 : 1) eluate gave 3-cyano-1-diethylphosphonooxy-2-methyl-1-cyclohexene (**4c**) (71 mg, 6%) as a colorless oil. IR ν_{max} cm^{-1}: 2220 (CN), 1655 (C=C), 1280 (P=O), 1050—960 (P–O–C). ^1H-NMR δ: 1.83 (3H, br s, CH_3), 3.46 (1H, br s, C_3-H). MS *m/e*: 259 (M^+). High-resolution MS Calcd for $C_{11}H_{18}NO_4P$: 259.0974. Found: 259.0971.

The second fraction of the benzene–EtOAc (10 : 1) eluate gave **3c** (654 mg, 51%) as a colorless oil. IR ν_{max} cm^{-1}: 2200 (CN), 1640 (C=C). ^1H-NMR δ: 2.05 (3H, br s, CH_3), 5.25 (1H, m, C_3-H). MS *m/e*: 259 (M^+). High-resolution MS Calcd for $C_{11}H_{18}NO_4P$: 259.0974. Found: 259.0972. When the cyanophosphorylation of **1c** (451 mg, 5 mmol) was carried out at room temperature, **4c** (522 mg, 40%) was obtained as a major product, together with **3c** (345 mg, 27%).

1-Cyano-3-diethylphosphonooxy-1-cyclopentene (**3d**): The crude extract, obtained by the general procedure *via* cyanophosphorylation of **1d** (246 mg, 3 mmol) at −17 °C, was purified by SiO_2 column chromatography. The first fraction of the benzene–EtOAc (20 : 1) eluate gave 3-cyano-1-diethylphosphonooxy-1-cyclopentene (**4d**) (79 mg, 11%) as a colorless oil. IR ν_{max} cm^{-1}: 2220 (CN), 1658 (C=C), 1260 (P=O), 1020—960 (P–O–C). ^1H-NMR δ: 3.63 (1H, br s, C_3-H), 5.32 (1H, br s, C_2-H). MS *m/e*: 245 (M^+). High-resolution MS Calcd for $C_{10}H_{16}NO_4P$: 245.0818. Found: 245.0815.

The second fraction of the benzene–EtOAc (10 : 1) eluate gave **3d** (465 mg, 64%) as a colorless oil. IR ν_{max} cm^{-1}: 2220 (CN), 1640 (C=C). ^1H-NMR δ: 5.50 (1H, br s, C_3-H), 6.67 (1H, br s, C_2-H). MS *m/e*: 245 (M^+). High-resolution MS Calcd for $C_{10}H_{16}NO_4P$: 245.0818. Found: 245.0816. When the cyanophosphorylation of **1d** (4.11 g, 50 mmol) was carried out at room temperature, **4d** (9.0 g, 74%) was obtained as a single product.

4-*tert*-Butyl-1-cyano-3-diethylphosphonooxy-1-cyclohexene (**9**): The crude extract, obtained by the general procedure from **7** (3.04 g, 20 mmol) *via* cyanophosphate (**8**), was purified by SiO_2 column chromatography with benzene–EtOAc (1 : 1) as the eluent. The first fraction gave 4-*tert*-butyl-1,2-dihydrobenzonitrile (**10**) (1.23 g, 38%) as a colorless oil. IR ν_{max} cm^{-1}: 2200 (CN), 1630 (C=C). ^1H-NMR δ: 1.12 [9H, br s, $C(CH_3)_3$], 2.30 (4H, br s, 2 × CH_2), 5.84, 6.67 (each 1H, each d, J = 7 Hz, 2 × CH). MS *m/e*: 161 (M^+). High-resolution MS Calcd for $C_{11}H_{15}N$: 161.1205. Found: 161.1204.

The second fraction gave a colorless oil (**9**) (3.21 g, 51%). IR ν_{max} cm^{-1}: 2220 (CN), 1635 (C=C). ^1H-NMR δ: 1.0 [9H, br s, $C(CH_3)_3$], 1.63 (1H, m, C_4-H), 4.93 [1H, m, irradiation of C_2-H collapsed to triplet of triplets (J = 7, 2.5 Hz), C_3-H], 6.71 (1H, br s, C_2-H). MS *m/e*: 315 (M^+). High-resolution MS Calcd for $C_{15}H_{26}NO_4P$: 315.1601. Found: 315.1598.

2-(1-Cyanoethylidene)-1-diethylphosphonooxycyclohexane (**16**): This was prepared by the general procedure from **14** *via* cyanophosphate (**15**) as a colorless oil in 79% yield. It was found to be a mixture of *Z*- and *E*-isomers in the ratio of 9 : 1. IR ν_{max} cm^{-1}: 2220 (CN), 1630 (C=C). ^1H-NMR δ: 1.94 (3H, br s, CH_3), 5.32 (br, C_2-H of *E*-isomer), 5.42 (br, C_2-H of *Z*-isomer). MS *m/e*: 287 (M^+). High-resolution MS Calcd for $C_{13}H_{22}NO_4P$: 287.1288. Found: 287.1285.

Dehydrogenation of 10——A solution of **10** (161 mg, 1 mmol) in dry toluene (10 ml) was refluxed with 10% Pd–C (800 mg) for 2 h. Removal of the catalyst by filtration and concentration of the filtrate *in vacuo* left a colorless oil, which was purified by SiO_2 column chromatography. The benzene–hexane (3 : 1) eluate gave 4-*tert*-butylbenzonitrile (102 mg, 65%). IR ν_{max} cm^{-1}: 2230 (CN), 1640 (C=C). ^1H-NMR δ: 1.33 [9H, s, $C(CH_3)_3$], 7.48, 7.59 (each 2H, each d,

J=9.3 Hz, 2×CH=CH). MS *m/e*: 159 (M^+). High-resolution MS Calcd for $C_{11}H_{13}N$: 159.1049. Found: 159.1047.

General Procedure for Hydrolysis of Allylic Phosphates (3 and 9)——A solution of an allylic phosphate (5 mmol) in 0.5 N HCl (50 ml) [EtOH (20 ml) was added as a co-solvent in the case of **9**] was refluxed. The reaction mixture was cooled to room temperature and extracted with benzene–EtOAc (1 : 1, 50 ml × 2) after saturation with NaCl. The extract was dried over Na_2SO_4, and concentrated *in vacuo* to leave an oil, which was purified by SiO_2 column chromatography with benzene–EtOAc (5 : 1) as eluent.

1-Cyano-3-hydroxy-2-methyl-1-cyclohexene (**5a**): This was prepared by the general procedure (reaction time 3 h) from **3a** as a colorless oil. IR ν_{max} cm^{-1}: 3400 (OH), 2200 (CN). ^{1}H-NMR δ: 1.92 (1H, br s, OH), 2.12 (3H, br s, CH_3), 4.12 (1H, br s, C_3-H). MS *m/e*: 137 (M^+). High-resolution MS Calcd for $C_8H_{11}NO$: 137.0841. Found: 137.0839.

1-Cyano-3-hydroxy-1-cyclohexene (**5b**): This was prepared by the general procedure (reaction time 3 h) from **3b** as a colorless oil. IR ν_{max} cm^{-1}: 3400 (OH), 2200(CN). ^{1}H-NMR δ: 2.23 (1H, br s, OH), 4.33 (1H, br s, C_3-H), 6.60 (1H, br s, C_2-H). MS *m/e*: 123 (M^+). High-resolution MS Calcd for C_7H_9NO: 123.0684. Found: 123.0683.

1-Cyano-3-hydroxy-2-methyl-1-cyclopentene (**5c**): This was prepared by the general procedure (reaction time 1.5 h) from **3c** as a colorless oil. IR ν_{max} cm^{-1}: 3400 (OH), 2220 (CN). ^{1}H-NMR δ: 2.04 (3H, br s, CH_3), 2.18 (1H, br s, OH), 4.72 (1H, br s, C_3-H). MS *m/e*: 123 (M^+). High-resolution MS Calcd for C_7H_9NO: 179.1311. Found: 179.1310.

1-Cyano-3-hydroxy-1-cyclopentene (**5d**): This was prepared by the general procedure (reaction time 2 h) from **3d** as a colorless oil. IR ν_{max} cm^{-1}: 3400 (OH), 2210 (CN). ^{1}H-NMR δ: 2.07 (1H, br s, OH), 5.01 (1H, br s, C_3-H), 6.65 (1H, br s, C_2-H). MS *m/e*: 109 (M^+). High-resolution MS Calcd for C_6H_7NO: 109.0528. Found: 109.0527.

cis-1-Cyano-4-*tert*-butyl-3-hydroxy-1-cyclohexene (**11**) and *trans*-1-Cyano-4-*tert*-butyl-3-hydroxy-1-cyclohexene (**12**): The crude extract obtained by the general procedure from **9** (2.52 g, 8 mmol) was purified by SiO_2 column chromatography. The first fraction of the benzene eluate gave **10** (310 mg, 24%), which was identical with an authentic sample (IR and ^{1}H-NMR spectral comparisons). The second fraction of the benzene–EtOAc (5 : 1) eluate gave a mixture of **11** and **12** (582 mg, 41%) in the ratio of 1 : 1 as judged from the ^{1}H-NMR spectrum. A mixture of **11** and **12** could be separated partially by SiO_2 column chromatography with benzene–EtOAc (10 : 1) as the eluent.

11: Colorless crystals of mp 80—81 °C (from ligroin). IR ν_{max}^{Nujol} cm^{-1}: 3450 (OH), 2215 (CN). ^{1}H-NMR δ: 1.02 [9H, br s, $C(CH_3)_3$], 1.15 (1H, ddd, J=13, 3.5, 2.5 Hz, C_4-H), 4.42 [1H, m, irradiation of C_2-H collapsed it to a doublet ($J_{3,4}$=3.5 Hz), C_3-H], 6.63 (1H, br s, C_2-H). MS *m/e*: 179 (M^+). High-resolution MS Calcd for $C_{11}H_{17}NO$: 179.1311. Found: 179.1310. *Anal.* Calcd for $C_{11}H_{17}NO$: C, 73.70; H, 9.56; N, 7.81. Found: C, 73.57; H, 9.63; N, 7.73.

12: A colorless oil. IR ν_{max} cm^{-1}: 3420 (OH), 2220 (CN). ^{1}H-NMR δ: 1.0 [9H, br s, $C(CH_3)_3$], 1.29 (1H, m, C_4-H), 4.26 [1H, br s, irradiation of C_2-H collapsed it to a doublet ($J_{3,4}$=8 Hz), C_3-H], 6.46 (1H, br s, C_2-H). MS m/*e*: 179 (M^+). High-resolution MS Calcd for $C_{11}H_{17}NO$: 179.1310. Found: 179.1311.

Hydrolysis of 16——A solution of **16** (2.80 g, 9.76 mmol) in 0.5 N HCl (90 ml) was refluxed for 1.5 h, then cooled to room temperature and extracted with benzene–EtOAc (1 : 1, 50 ml × 2) after saturation with NaCl. The extract was dried over anhyd. Na_2SO_4, and concentrated *in vacuo* to leave an oil, which was subjected to SiO_2 column chromatography. The first eluate with benzene gave a mixture of *Z*- and *E*-isomers of 3-(1-cyanoethylidene)-1-cyclohexene (**19**) (300 mg, 23%) as an oil. IR ν_{max} cm^{-1}: 2220 (CN), 1640, 1600 (C=C). ^{1}H-NMR δ: 1.65—1.80 (2H, m, CH_2), 1.92 (3H, s, CH_3), 2.20 (2H, m, CH_2), 2.40—2.50 (2H, m, CH_2), 6.16—6.25 (1H, m, 1-H), 6.41 (br d, J=9.8 Hz, 2-H of *E*-isomer), 6.65 (br d, J=10.4 Hz, 2-H of *Z*-isomer). MS *m/e*: 133 (M^+). High-resolution MS Calcd for $C_9H_{11}N$: 133.0892. Found: 133.0890. The second eluate with benzene–EtOAc (10 : 1) gave 2-(2′-hydroxy)cyclohexenylidenepropionic acid lactone (**18**) (290 mg, 19%) as an oil. IR ν_{max} cm^{-1}: 1750 (CO). ^{1}H-NMR δ: 1.81 (3H, d, J=2.7 Hz, CH_3), 4.58 (1H, m, CH). MS *m/e*: 152 (M^+). High-resolution MS Calcd for $C_9H_{12}O_2$: 152.0837. Found: 152.0835. The third eluate with benzene–EtOAc (5 : 1) gave 2-(1-cyanoethylidene)-1-cyclohexanol (**17**) (280 mg, 19%). IR ν_{max} cm^{-1}: 3400 (OH), 2210 (CN). ^{1}H-NMR δ: 1.60 (1H, br s, OH), 1.96 (3H, s, CH_3), 4.75 (1H, t, J=3.3 Hz, C_1-H). MS *m/e*: 151 (M^+). High-resolution MS Calcd for $C_9H_{13}NO$: 151.0998. Found: 151.0996.

Reaction of 17 with Diethyl Phosphorochloridate——*n*-Butyl lithium (15% hexane solution, 0.19 ml, 0.3 mmol) was added to a solution of diisopropylamine (30 mg, 0.3 mmol) in THF (1.5 ml) at −78 °C under N_2, and the mixture was stirred for 20 min at this temperature. A solution of **17** (45 mg, 0.3 mmol) in THF (2 ml) was added dropwise to this solution at −78 °C, and the reaction mixture was stirred for 20 min at −78 °C. After a solution of diethyl phosphorochloridate (62 mg, 0.36 mmol) in THF (2 ml) was added dropwise, the mixture was stirred for 30 min at −78——10 °C. The mixture was quenched by the addition of H_2O (0.5 ml), and the THF was removed by evaporation. The residue was extracted with benzene–EtOAc (1 : 1, 20 ml × 2), and the extract was washed with H_2O (10 ml), and brine (10 ml), then dried over anhyd. Na_2SO_4. Removal of the solvent gave an oil, which was purified by SiO_2 column chromatography. The eluate of benzene–EtOAc (10 : 1) gave *E*-**16** (65 mg, 76%) as an oil. IR ν_{max} cm^{-1}: 2220 (CN), 1630 (C=C). ^{1}H-NMR δ: 1.94 (3H, s, CH_3), 5.32 (1H, br s, 2-H). MS *m/e*: 287 (M^+).

General Procedure for Oxidation of Allylic Alcohols——A solution of an allylic alcohol (1 mmol) in $CHCl_3$ (10 ml) was stirred with MnO_2 (30 mmol) at room temperature. Removal of the MnO_2 by filtration and concentration of the filtrate left a colorless oil, which was purified by SiO_2 column chromatography with benzene as the eluent.

3-Cyano-2-methyl-2-cyclohexen-1-one (**6a**): This was prepared by the general procedure (reaction time 50 h) from **5a** as a colorless oil of bp_1 65—75 °C (Kugelrohr). IR ν_{max} cm^{-1}: 2220 (CN), 1685 (CO), 1610 (C=C). ^{1}H-NMR δ: 2.09 (3H, br s, CH_3), 2.50—2.62 (6H, m, 3×CH_2). MS *m/e*: 135 (M^+). High-resolution MS Calcd for C_8H_9NO:

135.0683. Found: 135.0684.

3-Cyano-2-cyclohexen-1-one (**6b**): This was prepared by the general procedure (reaction time 1.5 h) from **5b** as a colorless oil of bp_1 55—60 °C (Kugelrohr) (lit.[12] $bp_{0.5}$ 80 °C). IR ν_{max} cm^{-1}: 2200 (CN), 1685 (CO), 1600 (C=C). ^{1}H-NMR δ: 2.10—2.62 (6H, m, $3 \times CH_2$), 6.52 (1H, t, J=2 Hz, C_2-H). MS *m/e*: 121 (M^+). High-resolution MS Calcd for C_7H_7NO: 121.0528. Found: 121.0527.

3-Cyano-2-methyl-2-cyclopenten-1-one (**6c**): This was prepared by the general procedure (reaction time 5 d) from **5c** as a colorless oil of bp_1 55—60 °C (Kugelrohr) (lit.[13] mp 24—26 °C). IR ν_{max} cm^{-1}: 2210 (CN), 1710 (CO), 1625 (C=C). ^{1}H-NMR δ: 2.01 (3H, br s, CH_3), 2.52—2.82 (4H, m, $2 \times CH_2$). MS *m/e*: 121 (M^+). High-resolution MS Calcd for C_7H_7NO: 121.0528. Found: 121.0527.

3-Cyano-2-cyclopenten-1-one (**6d**): This was prepared by the general procedure (reaction time 8 h) from **5d** as a colorless oil of bp_2 55—60 °C (Kugelrohr) (lit.[14] bp_2 91—92 °C). IR ν_{max} cm^{-1}: 2210 (CN), 1715 (CO), 1590 (C=C). ^{1}H-NMR δ: 2.50—2.90 (4H, m, $2 \times CH_2$), 6.78 (1H, br s, C_2-H). MS *m/e*: 107 (M^+). High-resolution MS Calcd for C_6H_5NO: 107.0371. Found: 107.0370.

6-*tert*-Butyl-3-cyano-2-cyclohexen-1-one (**13**): This was prepared by the general procedure (reaction time 5 d) from the mixture of **11** and **12** in 75% yield as colorless crystals of mp 54—55 °C (from petr. ether). IR ν_{max}^{KBr} cm^{-1}: 2220 (CN), 1685 (CO), 1600 (C=C). ^{1}H-NMR δ: 1.05 [9H, br s, $C(CH_3)_3$], 1.86—2.62 (5H, m, $3 \times CH_2$), 6.43 (1H, br s, C_2-H). MS *m/e*: 177 (M^+). *Anal.* Calcd for $C_{11}H_{15}NO \cdot 1/8\,H_2O$: C, 73.61; H, 8.56; N, 7.80. Found: C, 73.78; H, 8.50; N, 7.67.

2-(1-Cyanoethylidene)-1-cyclohexanone (**20**): This was prepared by the general procedure (reaction time 10 d) from **17** in 68% yield as colorless crystals of mp 41—42 °C (from ligroin–petr. ether). IR ν_{max}^{Nujol} cm^{-1}: 2210 (CN), 1700 (CO), 1610 (C=C). ^{1}H-NMR δ: 2.06 (3H, br s, CH_3), 1.84—2.85 (8H, m, $4 \times CH_2$). MS *m/e*: 149 (M^+). *Anal.* Calcd for $C_9H_{11}NO$: C, 72.45; H, 7.43; N, 9.39. Found: C, 72.40; H, 7.38; N, 9.20.

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