Three-Component Coupling of Acylphosphonates and Two Carbonyl Compounds Promoted by Low-Valent Samariums: One-Pot Synthesis of β-Hydroxyphosphonates

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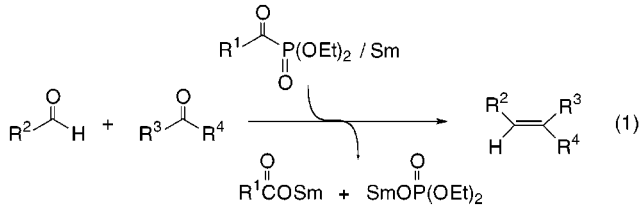
Three-component coupling of acylphosphonates and two carbonyl compounds leading to β-hydroxyphosphonates has been achieved with low-valent samariums. Thus, acylphosphonates reacted with aldehydes in the presence of semicatalytic amounts of samarium metal or SmI_2 to give acyloxyphosphonates in good yields. The second coupling reaction of the acyloxyphosphonates with aldehydes or ketones promoted by SmI_2 afforded β-hydroxyphosphonates instead of olefins. Moreover, these two reactions could be carried out in one pot.

Introduction

Deoxygenative coupling of carbonyl compounds leading to substituted olefins is an important process in organic synthesis that can be promoted by various low-valent metals and metal complexes.[1] However, of the metals, lanthanides have been rarely used for this transformation despite their strong reducing ability and oxophilicity. The reaction with SmI_2 has been known to produce pinacols, but further deoxygenation could not be accomplished.[2] Reductive homologation of CO mediated by $(C_5Me_5)_2Sm(thf)_2$ did not include deoxygenation formally.[3] It has been also reported that treatment of diaryl ketones with lanthanide metals (Yb, Sm) gave dianion complexes, $[Ln(OCAr_2)(hmpa)_2]_2$, which were reduced further with the excess metals to afford μ-diarylmethylidene intermediates instead of the coupling products.[4] Only the SmI_2−Sm system succeeded in the transformation of amides to yield *vic*-diaminoolefins.[5]

To achieve the deoxygenative coupling of ketones and aldehydes by low-valent lanthanides, we planned an indirect method by using acylphosphonates and Sm metal or SmI_2, in which one oxygen would be eliminated as a carboxylic acid and the other as a phosphate (eq 1). That



(1)

is, this scenario constitutes three individual steps as shown in Scheme 1: (i) reaction of acylphosphonates with aldehydes to yield acyloxyphosphonates, (ii) reductive elimination of carboxylic acids, followed by coupling with ketones, and (iii) Horner−Emmons olefination. With respect to the first step, we have previously reported that the C−P bond of acylphosphonates was readily cleaved by Yb and Sm metals to generate lanthanide phosphonates.[6] Reductive elimination of the carboxylic acid in the second step would also be facile on the analogy of many α-oxygenated ketones and esters being reduced with SmI_2.[2] Moreover, if each step proceeds successively, the overall reaction could be carried out in one pot.

With such consideration in mind, we investigated these reactions and found that the former two reactions worked well, but the third Horner−Emmons reaction did not. Consequently, the overall reaction produced β-hydroxyphosphonates in good yields, which were, of course, converted to the expected olefins by treatment with other bases. We describe herein these results.

Results and Discussion

At first, reaction of diethyl *p*-toluoyl- and benzoylphosphonates (**1a** and **1b**) with benzaldehyde was investi-

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(2) (a) Imamoto, T. *Lanthanides in Organic Synyhesis*; Academic Press: London, 1994. (b) Molander, G. A. *Chem. Rev.* **1992**, *92*, 29−68. (c) Molander, G. A. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. 1, pp 251−282.

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Scheme 1

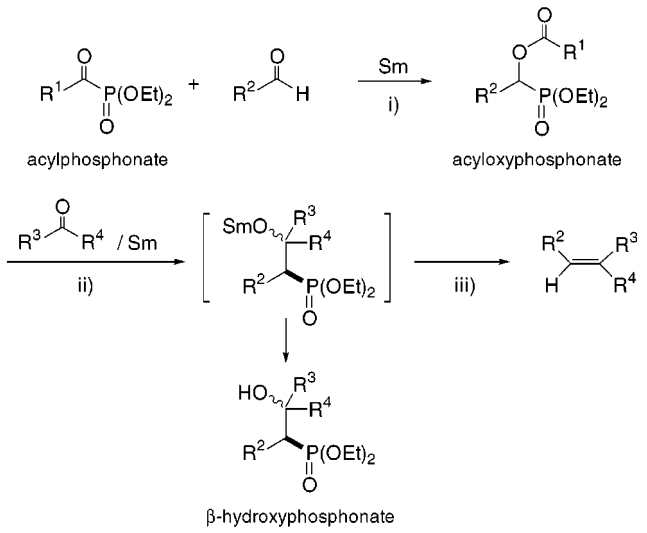
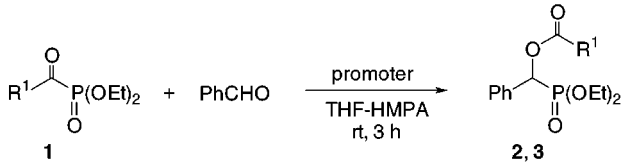


Table 1. Reaction of Acylphosphonates 1 with Benzaldehyde[a]



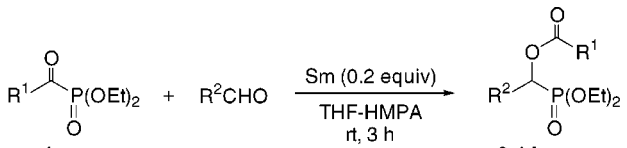
run	acylphosphonate 1 (R^1)		promoter (equiv)		product	yield (%)[b]
1	**1a**	*p*-MeC_6H_6	Sm	(1)	**2**	72
2[c]	**1a**		Sm	(1)	**2**	7
3	**1a**		Sm	(0.2)	**2**	77
4	**1a**		Sm	(0.1)	**2**	72
5	**1a**		Yb	(1)	**2**	58
6	**1b**	Ph	Sm	(0.2)	**3**	85
7	**1b**		SmI_2	(0.2)	**3**	80
8	**1b**		$Sm(O^iPr)_3$	(0.2)	no reaction	
9	**1b**		Na	(0.2)	**3**	37
10	**1b**		Li	(0.2)	**3**	26

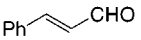
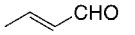
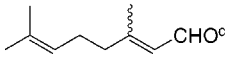
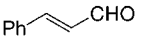
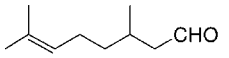
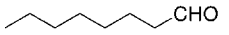
[a] 4 equiv of benzaldehyde was used. [b] GC yield based on **1**.
[c] 1 equiv of benzaldehyde was used.

gated (Table 1). Acyloxyphosphonate **2** was formed in 72% yield from **1a** by using 4 equiv of the aldehyde and a stoichiometric amount of Sm metal (run 1).[7] Use of an excess of the aldehyde is crucial in this reaction. Thus, the yield of **2** decreased to 7% with an equimolar amount of benzaldehyde (run 2), which should be attributed to the homocoupling reaction of the acylphosphonate **1a**.[6] Less loading of Sm metal showed similar results (runs 3 and 4), but substitution of Sm by Yb metal caused a decrease of the yield (run 5). In the reaction of benzoylphosphonate **1b**, the effect of various promoters (0.2 equiv) was tested. SmI_2 was comparable to Sm metal (runs 6 and 7), whereas $Sm(O^iPr)_3$ did not promote the reaction (run 8). The product **3** was obtained in lower yields with Na and Li (runs 9 and 10).

(7) When the solvent, THF−HMPA (4/1), was changed to THF−1,3-dimethyl-2-imidazolidinone (4/1), THF−1,1,3,3-tetramethylurea (4/1), or THF only, the yield of **2** decreased to 13%, 27%, or 25% yields, respectively.

Table 2. Preparation of Acyloxyphosphonates 2−14[a]



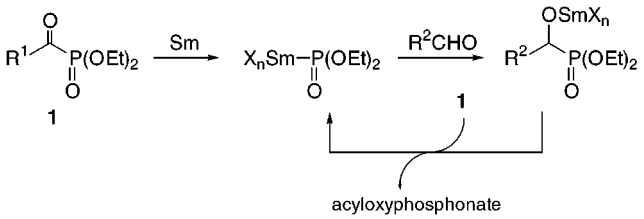
run	acylphosphonate 1 (R^1)		aldehyde	product	yield (%)[b]
1	**1a**	*p*-MeC_6H_4	PhCHO	**2**	77
2	**1b**	Ph	PhCHO	**3**	85
3	**1c**	*p*-$MeOC_6H_4$	PhCHO	**4**	81 (67)
4	**1d**	*p*-ClC_6H_4	PhCHO	**5**	97 (83)
5	**1e**	^{i}Pr	PhCHO	no reaction	
6	**1b**	Ph	*p*-MeC_6H_4CHO	**6**	95 (61)
7	**1b**			**7**	99 (94)
8	**1b**			**8**	95 (65)
9	**1b**			**9**[d]	71 (65)
10	**1b**		^{i}PrCHO	**10**	91 (77)
11	**1b**		^{n}PrCHO	**11**	87 (67)
12	**1d**	*p*-ClC_6H_4		**12**	92 (90)
13	**1d**			**13**[e]	(89)
14	**1d**			**14**	(57)

[a] 4 equiv of aldehyde was used. [b] GC yield (isolated yield) based on **1**.
[c] (E) / (Z) = 61 / 39. [d] (E) / (Z) = 70 / 30. [e] A mixture of 52 / 48 ratio.

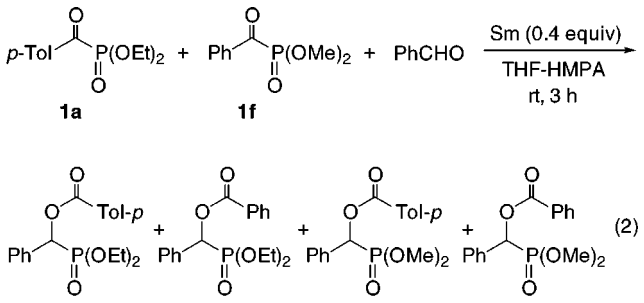
Next, acyloxyphosphonates **2**−**14** were prepared from various acylphosphonates **1** and aldehydes, and these results are summarized in Table 2. Aromatic acylphosphonates **1a**−**d** reacted with benzaldehyde to give the products **2**−**5** in high yields, wherein electron-withdrawing substituents caused better yields than electron-donating ones (runs 1−4). However, no reaction took place with aliphatic acylphosphonate **1e** (run 5). Aromatic, α,β-unsaturated, and aliphatic aldehydes were readily converted to the corresponding phosphonates **6**−**14** (runs 6−14). In contrast, the reaction of **1** with ketones did not afford the acyloxyphosphonates, in which a different type of reaction seemed to proceed.[8]

The coupling reaction described above would be explained as shown in Scheme 2. Addition of samarium phosphonate, which is generated by the reduction of **1** with Sm or SmI_2,[6] to aldehyde affords samarium alkox-

Scheme 2

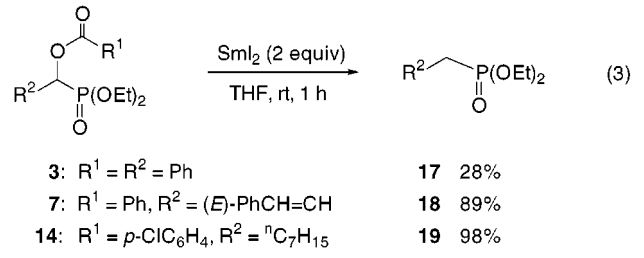


ide.[9] Abstraction of the acyl group from **1** by the alkoxide results in the formation of acyloxyphosphonate and regeneration of the phosphonate anion. In fact, intermolecular acyl transfer was proved by the competitive reaction between the two acyphosphonates **1a** and **1f** (eq 2). When an equimolar mixture of **1a** and **1f** was treated



with excess benzaldehyde (8 equiv) in the presence of Sm metal (0.4 equiv), all homo and cross-coupling products **2**, **3**, **15**, and **16** were formed in 70% total yield with a ratio of 29:16:9:46.

Next, reductive elimination of carboxylic acids from the acyloxyphosphonates was investigated (eq 3). Treatment



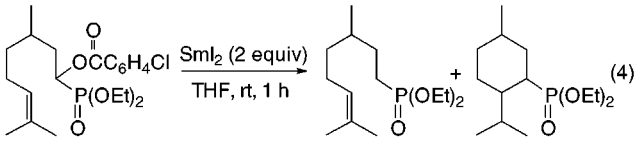
of **7** with SmI_2 (2 equiv) gave the reduced phosphonate **18** in 89% yield.[10] Acyloxyphosphonate **14** was similarly changed to **19** in high yield, whereas the reduction of **3** gave benzylphosphonate **17** in lower yield along with many unidentified products. In all reactions, no deuterium was incorporated in products **17**−**19** on quenching with D_2O, indicating that radicals, generated in situ, were not reduced further to α-phosphono carbanions.

(8) For example, the reaction of **1a** with benzophenone in the presence of Sm metal (1 equiv) gave diphenylmethyl tolyl ketone and diphenylhydroxymethyl tolyl ketone in 73% and 20% yields, respectively. 2-Adamantyl phenyl ketone was prepared in 30% yield from **1b** and 2-adamantanone. However, the reaction with ketones having α-hydrogens such as cyclohexanone gave a complex mixture.

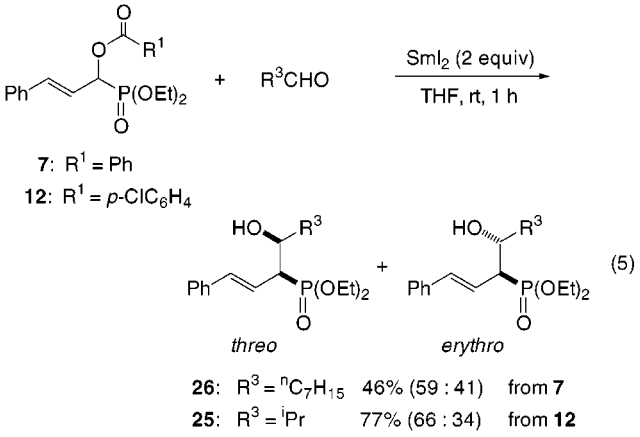
(9) Asymmetric hydrophosphonylation of aldehydes and imines catalyzed by chiral heterobimetallic lanthanides has been reported: Shibasaki, M.; Groger, H. In *Lanthanides: Chemistry and Use in Organic Synthesis*; Kobayashi, S., Ed.; Springer: Berlin, 1999; pp 199−232 and references therein.

(10) In the reaction with an equimolar amount of SmI_2, **18** was formed in 51% yield, and **7** was recovered in 21% yield.

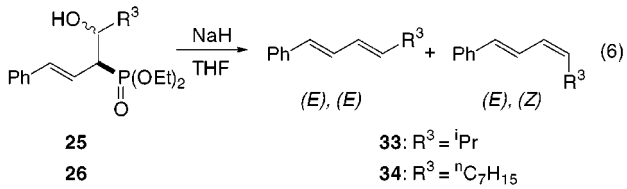
Moreover, the reaction of **13** afforded **20** and cyclic product **21** in 42% and 32% yields, respectively, eq 4).



On the basis of the above results, reduction of the acyloxyphosphonates should be carried out in the presence of the second carbonyl compound as a radical trapping agent in order to achieve an effective three-component coupling. Thus, a mixture of **7** and octanal (1.2 equiv) was treated with SmI_2 (2 equiv) to give β-hydroxyphosphonate **26** in 46% yield with a diastereomer ratio of 59:41 (eq 5). Similarly, the phosphonate **25**



was obtained in 77% yield (66:34) by the reaction of **12** with isobutylaldehyde. Stereochemistry of the diastereomers was determined as follows (eq 6). While the major

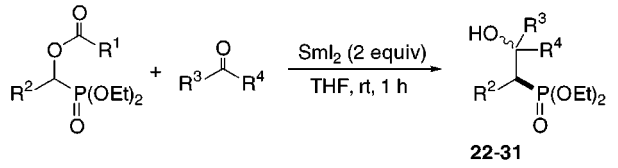


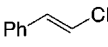
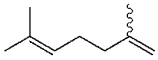
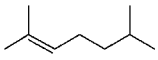
threo-**25**: -15 °C, 2 h,94% (100 : 0) *erythro*-**25**: -15 °C, 6 h,98% (42 : 58)
threo-**26**: rt, 0.5 h, 95% (98 : 2) *erythro*-**26**: rt, 2.5 h, 86% (76 : 24)

diastereomers of **25** and **26** were selectively changed to (*E*,*E*)-dienes **33** and **34**, respectively, on treatment with NaH, conversion of the minor isomers was slow and nonstereoselective, which is probably a result of epimerization before the Horner−Emmons reaction. Therefore, the major isomers were assigned to *threo* and the minor to *erythro*. Attempts to produce the olefins directly from the acyloxyphosphonates and carbonyl compounds without NaH by excess use of SmI_2 (4 equiv), elevated temperature (refluxing), and a polar solvent (THF−HMPA) were unsuccessful. The reason for this failure is not clear at present.

Results on the coupling reaction of various acyloxyphosphonates with carbonyl compounds are summarized in Table 3. Both ketones and aldehydes gave β-hydroxyphosphonates **22**−**31** in fairly good yields, except for

Table 3. Preparation of β-Hydroxyphosphonates 22−31 from Acyloxyphosphonates and Ketones or Aldehydes[a]

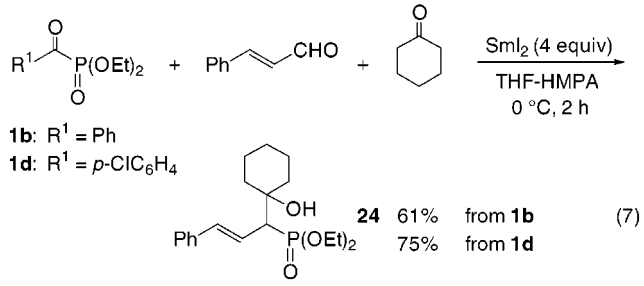


run	acyloxyphosphonate	(R^1)	(R^2)	ketones or aldehydes	product	yield (%)[b] *threo* : *erytho*
1	**3**	Ph	Ph		**22**	76 (63)
2	**3**			^{i}PrCHO	**23**	(63) 70 : 30
3	**7**	Ph	Ph		**24**	68 (64)
4	**7**			^{i}PrCHO	**25**	(75) 66 : 34
5	**7**			$^nC_7H_{15}CHO$	**26**	(46) 59 : 41
6	**7**			*p*-ClC$_6$H$_4$CHO	many products	
7	**7**				many products	
8[c]	**8**	Ph		$^nC_7H_{15}CHO$	**27**	(42) 54 : 46
9	**9**	Ph			**28**	(65)
10	**9**			$^nC_7H_{15}CHO$	**29**	(62) – [d]
11	**12**	*p*-ClC$_6$H$_4$	Ph	^{i}PrCHO	**25**	82 (77) 66 : 34
12	**13**	*p*-ClC$_6$H$_4$			**30**	(48)
13	**14**	*p*-ClC$_6$H$_4$	$^nC_7H_{15}$		**31**	70 (40)[e]

[a] 1.2 equiv of ketone or aldehyde was used. [b] GC yield (isolated yield) based on the acyloxyphosphonate. [c] $^nC_7H_{15}CH(OH)CH(Me)CH{=}CHP(O)(OEt)_2$ **27'** was also obtained in 21% yield. [d] Not determined. [e] Isolated as a dehydrated product **31'**.

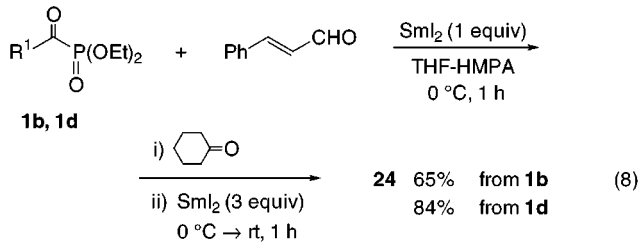
aromatic and α,β-unsaturated aldehydes (runs 6 and 7). The reaction with these aldehydes produced many byproducts, including pinacols, because they were reduced with SmI_2 at a rate comparable to that of the acyloxyphosphonates. In the reaction of **8** with octanal, a coupling reaction took place at the α- and γ-positions to the phosphonate group, giving rise to **27** and **27′** in 42% and 21% yields, respectively (run 8). For the reaction of acyloxyphosphonates **13** and **14** derived from aliphatic aldehydes (R^2 = alkyl), the *p*-ClC_6H_4 group showed better results than did Ph as the substituent R^1 (runs 12 and 13). However, stereoselectivity was not changed by the two leaving groups (runs 4 and 11).

Because it has been found that the two reactions described above can be promoted by low-valent samariums, we investigated the one-pot reaction of the three-component coupling with SmI_2. Initially, acylphosphonate **1b** or **1d**, cinnamaldehyde, and cyclohexanone were used as model substrates. The reaction was carried out by two different methods: one is a one-step procedure (method A, eq 7), and the other is a two-step procedure (method



(7)

B, eq 8). When a mixture of **1b**, the aldehyde, and ketone

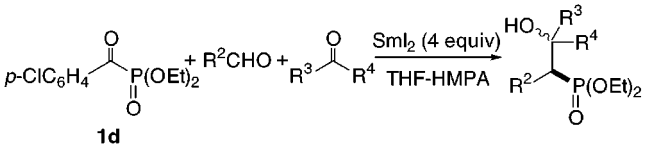


(8)

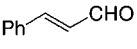
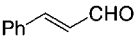
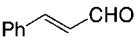
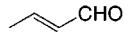
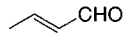
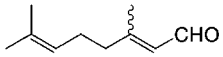
(1:2:0.8) was treated with SmI_2 (4 equiv of **1b**) (method A), β-hydroxyphosphonate **24** was obtained in 61% yield, which is slightly lower than the expected yield (67%) based on the individual steps (Table 2, run 7 and Table 3, run 3). The yield of **24** was increased to 75% by using the acylphosphonate **1d**, wherein (*E*)-cinnamylphosphonate **18** was also formed as a byproduct in 25% yield based on **1d**. Thus, it is clear that acylphosphonates **1b** and **1d** react exclusively with cinnamaldehyde in the first step and their reaction with cyclohexanone is suppressed. However, in the second step, the resulting acyloxyphosphonates **7** and **12** coupled selectively with cyclohexanone and not with cinnamaldehyde, despite its excess use. The two-step reaction (method B) gave the β-hydroxyphosphonate **24** in 65% yield from **1b** and 84% yield from **1d** (eq 8).

The one-pot reaction was carried out with various ketones and aldehydes by using acylphosphonate **1d**, and these results are given in Table 4. As a whole, the two-step reaction (method B) was superior to the one-step reaction (method A), affording β-hydroxyphosphonates in yields comparable to those obtained by the stepwise coupling (Tables 2 and 3). In the reaction by method A, there is a restriction on the combination of the two carbonyl compounds. When cyclohexanone and isobutylaldehyde were used as coupling partners of aromatic and α,β-unsaturated aldehydes (runs 1−3, 5, and 7), decrease of the yields was not so severe compared with the results by method B, except for run 5. In contrast, the reaction with octanal gave the β-hydroxyphosphonates **26** and **27** in low yields (runs 4 and 6). For example, the reaction of **1d** with cinnamaldehyde and octanal gave **26**, acyloxyphosphonate **12**, and octylphosphonate **19** in 26%, 22%, and 52% yields, respectively, wherein three possible β-hydroxyphosphonates other than **26** were not obtained (run 4). This result suggests that **1d** reacts with the two aldehydes competitively, but the resulting acyloxyphosphonate **14** derived from octanal does not couple with another molecule of octanal or cinnamaldehyde. In the reaction with octanal and cyclohexanone, the second coupling did not proceed effectively by either method, despite facile formation of the acyloxyphosphonate **14**

Table 4. One-Pot Reaction of Acyloxyphosphonate 1d and Two Carbonyl Compounds[a]



1d

run	R^2CHO	R^3R^4CO	product	method A[b] yield (%)[d]	Method B[c] yield (%)[d]
1	PhCHO		**22**	49	(64)
2			**24**	75 (42)	84 (67)
3		^iPrCHO	**25**	71 61 : 39[e]	83 63 : 37[e]
4		$^nC_7H_{15}CHO$	**26**	26	(67) 57 : 43[e]
5			**32**	44	71 (54)
6		$^nC_7H_{15}CHO$	**27**	14	(39)
7			**28**	80	90 (71)
8	$^nC_7H_{15}CHO$		**31**[f]	30	39

[a] Conditions: **1d** / R^2CHO / R^3R^4CO / SmI_2 = 1 / 2 / 0.8 / 4. [b] One-step reaction. [c] Two-step reaction. [d] GC yield (isolated yield) based on R^3R^4CO. [e] Ratio of *threo* to *erythro*. [f] Isolated as a dehydrated product **31′**.

from **1d** and octanal (run 8). Thus, β-hydroxyphosphonate **31** was obtained in 30% yield by method A and 39% yield by method B along with octylphosphonate **19** in 70% and 61% yields, respectively.

In summary, three-component coupling of acylphosphonates and two carbonyl compounds was accomplished with low-valent samariums to give β-hydroxyphosphonates, versatile intermediates, in fairly good yields. The present reaction is unprecedented and would provide a potentially useful method for the preparation of the hydroxyphosphonates despite a failure in their direct transformation to olefins, because the reaction can be performed in one pot.

Experimental Section

General. ^1H and ^{13}C NMR spectra were recorded at 400 and 99 MHz, respectively. IR spectra were taken on a FT-IR spectrophotometer. Mass spectra were obtained at 70 eV on a GC−MS apparatus. Microanalyses were performed at our analytical laboratory. All reactions were carried out under argon. THF was distilled from sodium/benzophenone ketyl immediately prior to use. HMPA was distilled from CaH_2 and stored over molecular sieves. Samarium and ytterbium metals (40 mesh) were washed with anhydrous hexane under argon and dried in vacuo. SmI_2 (0.1 M in THF) was prepared by the reported method.[11] Acylphosphonates **1** were prepared conventionally from the corresponding acid chlorides and triethyl phosphite.[12] All other materials were commercially available and were used after distillation.

General Procedure for the Reaction of Acylphosphonates 1 with Aldehydes. Samarium metal (30 mg, 0.2 mmol) was heated for 10 min in vacuo. After the mixture cooled to room temperature, THF (1 mL) and HMPA (1 mL) were added to the metal. Then, diiodomethane (3 μL) was injected into the mixture to activate the metal. A solution of acylphosphonate **1** (1 mmol) and aldehyde (4 mmol) in THF (3 mL) was added to the mixture. The slurry was stirred for 3 h at room temperature to give a homogeneous brown solution, which was quenched with water (2 mL) and then hydrochloric acid (2 M, 5 mL). After addition of an internal standard such as heptadecane for GC analysis, the mixture was extracted with ether, washed with brine, dried over $MgSO_4$, and concentrated in vacuo. Acyloxyphosphonates **2**−**14** were isolated by column chromatography on silica gel with hexanes/EtOAc eluent. Large-scale reaction, for example, using 30 mmol of **1**, could be performed in a more concentrated solution (0.6 M, THF/HMPA = 4/1). The reactions with other promoters were carried out similarly. In the competitive reaction between **1a** and **1f** with benzaldehyde (eq 2), the four products **2**, **3**, **15**, and **16** were isolated as a mixture by column chromatography on silica gel, and their ratio was determined by ^1H NMR and GC.

General Procedure for the Reduction of Acyloxyphosphonates 3, 7, 13, and 14 with SmI_2. SmI_2 (0.1 M in THF, 10 mL) was added to a solution of the acyloxyphosphonate (0.5 mmol) in THF (3 mL) at room temperature, and stirring was continued for 1 h. The reaction was quenched with water (5 mL), and tridecane was added to the mixture as an internal standard. Then, the mixture was extracted with ether, washed with sodium hydrogensulfite solution and brine, dried over $MgSO_4$, and concentrated in vacuo. The residue was chromatographed on silica gel with hexanes/EtOAc eluent to give **17** (28% from **3**), **18** (69% from **7**), or **19** (70% from **14**). In the reaction of **13**, **20** and **21** were isolated in 34% and 20% yields, respectively.

General Procedure for the Reaction of Acyloxyphosphonates with Ketones or Aldehydes. SmI_2 (0.1 M in THF, 20 mL) was added to a solution of the acyloxyphosphonate (1 mmol) and ketone or aldehyde (1.2 mmol) in THF (2 mL), and the mixture was stirred for 1 h at room temperature. The reaction was quenched with water (10 mL) and hydrochloric acid (2 M, 10 mL). After addition of tridecane as an internal standard, the mixture was extracted with ether, washed with sodium hydrogensulfite solution and brine, and dried over $MgSO_4$. Concentration of the mixture left a yellow residue, which was chromatographed on silica gel with hexanes/EtOAc eluent to give β-hydroxyphosphonate. When the reaction produced two diastereomers, their ratio was determined by ^1H and ^{13}C NMR spectra of the crude mixture. Although the two diastereomers showed a single peak on GC, they were separable by column chromatography; the major diastereomer (*threo*) was eluted first, except for **23**. ^1H NMR spectra of the major diastereomer exhibited coupling constants (8.6−9.9 Hz) between C*H*(OH)−C*H*(P) larger than those of the minor diastereomer (1.2−2.6 Hz). In the reaction of **14** with cyclohexanone, the initial product, diethyl 1-(1′-hydroxycyclohexyl)-octylphosphonate (**31**), was dehydrated by the column chromatography to give diethyl 1-(1′-cyclohexenyl)octylphosphonate (**31′**).

Diethyl 1-(1′-Hydroxycyclohexyl)benzylphosphonate (22). Colorless solid; R_f = 0.44 (silica gel, hexane/EtOAc = 1/1); IR (Nujol) 3424, 1211, 1030 cm^{-1}; MS *m/z* 311 (M^+ − Me), 285, 272, 257, 230, 173; ^1H NMR ($CDCl_3$) δ 0.91 (3H, t, J = 6.9 Hz), 1.20−1.94 (10H, m), 1.32 (3H, t, J = 6.9 Hz), 3.32 (1H, d, J = 23.8 Hz), 3.37−3.52 (1H, m), 3.75−3.89 (1H, m), 3.99−4.23 (3H, m), 7.10−7.57 (5H, m); ^{13}C NMR ($CDCl_3$) δ 15.8 (d, J = 6.1 Hz), 16.2 (d, J = 6.2 Hz), 21.8, 22.1, 25.4, 35.9 (d, J = 10.9 Hz), 38.8 (d, J = 3.6 Hz), 53.7 (d, J = 131.9 Hz), 61.1 (d, J = 8.6 Hz), 63.2 (d, J = 7.4 Hz), 72.9 (d, J = 3.6 Hz), 127.1 (d, J = 2.4 Hz), 128.1 (two carbons), 134.2 (d, J = 4.9 Hz). Anal. Calcd for $C_{17}H_{27}O_4P$: C, 62.56; H, 8.34. Found: C, 62.26; H, 8.33.

(11) Girard, P.; Namy, J. L.; Kagan, H. B. *J. Am. Chem. Soc.* **1980**, *102*, 2693−2698.

(12) Kabachnik, M. I.; Rossiiskaya, P. A. *Bull. Acad. Sci. URSS, Cl. Sci. Chim.* **1945**, 367−374; *Chem. Abstr.* **1946**, *40*, 4688.

Diethyl 2-Hydroxy-3-methyl-1-phenylbutylphosphonate (23) [142465-88-1]. (*threo*-Isomer, major): colorless solid; R_f = 0.24 (silica gel, hexane/EtOAc = 1/1); IR (Nujol) 3328, 1224, 1029 cm^{-1}; MS *m*/*z* 230, 202, 92; ^{1}H NMR ($CDCl_3$) δ 0.79 (3H, d, *J* = 6.6 Hz), 0.96 (3H, d, *J* = 6.9 Hz), 1.16 (3H, t, *J* = 7.1 Hz), 1.27 (3H, t, *J* = 6.9 Hz), 1.46−1.51 (1H, m), 3.23 (1H, dd, *J* = 20.8 and *9.9* Hz), 3.81−4.23 (6H, m), 7.23−7.34 (5H, m); ^{13}C NMR ($CDCl_3$) δ 13.6, 16.2 (d, *J* = 6.2 Hz), 16.3 (d, *J* = 6.1 Hz), 20.1, 29.6 (d, *J* = 13.4 Hz), 49.5 (d, *J* = 134.2 Hz), 62.2 (d, *J* = 7.4 Hz), 62.8 (d, *J* = 6.1 Hz), 74.9 (d, *J* = 4.8 Hz), 127.2 (d, *J* = 2.5 Hz), 128.4 (d, *J* = 2.5 Hz), 129.5 (d, *J* = 6.1 Hz), 134.6 (d, *J* = 7.3 Hz). Anal. Calcd for $C_{15}H_{25}O_4P$: C, 60.00; H, 8.40. Found: C, 59.78; H, 8.46. (*erythro*-Isomer, minor): yellow oil; R_f = 0.27 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3406, 1231, 1028 cm^{-1}; MS *m*/*z* 230, 202, 91; ^{1}H NMR ($CDCl_3$) δ 0.84 (3H, d, *J* = 6.9 Hz), 0.97 (3H, t, *J* = 6.9 Hz), 0.99 (3H, d, *J* = 6.6 Hz), 1.35 (3H, t, *J* = 7.1 Hz), 1.44−1.57 (1H, m), 3.30 (1H, dd, *J* = 25.4 and *2.6* Hz), 3.52 (1H, ddd, *J* = 14.9, 7.3, and 2.6 Hz), 3.78−3.93 (3H, m), 4.06−4.23 (2H, m), 7.28−7.36 (3H, m), 7.49−7.53 (2H, m); ^{13}C NMR ($CDCl_3$) δ 16.0 (d, *J* = 6.1 Hz), 16.3 (d, *J* = 6.1 Hz), 18.9, 31.0 (d, *J* = 2.5 Hz), 47.2 (d, *J* = 135.5 Hz), 61.8 (d, *J* = 7.3 Hz), 63.4 (d, *J* = 7.3 Hz), 75.9 (d, *J* = 3.7 Hz), 127.3 (d, *J* = 3.7 Hz), 128.4 (d, *J* = 2.5 Hz), 130.7 (d, *J* = 7.4 Hz), 132.8 (d, *J* = 4.9 Hz).

Diethyl 1-(1′-Hydroxycyclohexyl)cinnamylphosphonate (24). Yellow oil; R_f = 0.41 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3394, 1601, 1226, 1025 cm^{-1}; MS *m*/*z* 335 (M^+ − OH), 253 ($M^+ - C_6H_{10}OH$), 198 (335 − $OP(OEt)_2^+$); ^{1}H NMR ($CDCl_3$) δ 1.09−1.84 (11H, m), 1.27 (3H, t, *J* = 6.9 Hz), 1.34 (3H, t, *J* = 6.9 Hz), 2.87 (1H, dd, *J* = 21.1 and 10.6 Hz), 4.04−4.21 (4H, m), 6.21 (1H, ddd, *J* = 15.8, 10.6, and 5.6 Hz), 6.48 (1H, dd, *J* = 15.8 and 4.8 Hz), 7.22−7.46 (5H, m); ^{13}C NMR ($CDCl_3$) δ 16.3 (d, *J* = 2.4 Hz), 16.4 (d, *J* = 3.7 Hz), 21.6, 21.8, 25.4, 35.2 (d, *J* = 8.5 Hz), 37.6 (d, *J* = 5.6 Hz), 53.7 (d, *J* = 131.8 Hz), 61.9 (d, *J* = 7.3 Hz), 62.5 (d, *J* = 6.1 Hz), 72.4 (d, *J* = 4.9 Hz), 122.3 (d, *J* = 10.9 Hz), 126.3, 127.7, 128.6, 135.1 (d, *J* = 13.4 Hz), 136.8. Anal. Calcd for $C_{19}H_{29}O_4P$: C, 64.76; H, 8.29. Found: C, 64.70; H, 8.25.

Diethyl 4-Hydroxy-5-methyl-1-phenyl-1(*E*)-hexen-3-ylphosphonate (25) [160723-17-1]. (*threo*-Isomer, major): yellow oil; R_f = 0.21 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3328, 1599, 1230, 1029 cm^{-1}; MS *m*/*z* 255, 227, 198, 116; ^{1}H NMR ($CDCl_3$) δ 0.88 (3H, d, *J* = 6.6 Hz), 1.04 (3H, d, *J* = 6.9 Hz), 1.33 (6H, t, *J* = 7.0 Hz), 1.75−1.87 (1H, m), 2.88 (1H, dt, *J* = 19.1 and *9.9* Hz), 3.88 (1H, ddd, *J* = 12.5, 9.9, and 3.0 Hz), 4.07−4.23 (5H, m), 5.97 (1H, ddd, *J* = 15.8, 9.9, and 5.6 Hz), 6.51 (1H, dd, *J* = 15.8 and 5.0 Hz), 7.22−7.48 (5H, m); ^{13}C NMR ($CDCl_3$) δ 13.6, 16.4 (d, *J* = 6.1 Hz), 16.5 (d, *J* = 6.1 Hz), 20.1, 30.6 (d, *J* = 3.4 Hz), 47.6 (d, *J* = 134.3 Hz), 62.4 (d, *J* = 6.1 Hz), 62.8 (d, *J* = 7.3 Hz), 73.7 (d, *J* = 6.1 Hz), 121.7 (d, *J* = 12.2 Hz), 126.3, 127.8, 128.6, 133.9 (d, *J* = 13.4 Hz), 136.7. Anal. Calcd for $C_{17}H_{27}O_4P$: C, 62.56; H, 8.34. Found: C, 62.39; H, 8.07. (*erythro*-Isomer, minor): yellow oil; R_f = 0.16 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3382, 1230, 1026 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.84 (3H, d, *J* = 6.6 Hz), 1.04 (3H, d, *J* = 6.6 Hz), 1.25 (3H, t, *J* = 7.0 Hz), 1.36 (3H, t, *J* = 7.1 Hz), 1.59−1.80 (2H, m), 2.98 (1H, ddd, *J* = 24.2, 10.1 and *1.2* Hz), 3.72 (1H, dt, *J* = 1.2 and 8.6 Hz), 4.01−4.24 (4H, m), 6.38 (1H, ddd, *J* = 16.0, 10.1, and 5.8 Hz), 6.57 (1H, dd, *J* = 16.0 and 5.1 Hz), 7.21−7.58 (5H, m); ^{13}C NMR ($CDCl_3$) δ 16.4 (d, *J* = 6.1 Hz), 18.5, 19.4, 31.6 (d, *J* = 11.6 Hz), 45.8 (d, *J* = 136.8 Hz), 62.1 (d, *J* = 7.3 Hz), 63.4 (d, *J* = 7.4 Hz), 75.2 (d, *J* = 6.1 Hz), 119.6 (d, *J* = 8.6 Hz), 126.3, 127.7, 128.6, 135.5 (d, *J* = 13.4 Hz), 136.8.

Diethyl 4-Hydroxy-1-phenyl-1(*E*)-undecen-3-ylphosphonate (26). (*threo*-Isomer, major): yellow oil; R_f = 0.43 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3402, 1601, 1225, 1027 cm^{-1}; MS *m*/*z* 365 (M^+ − OH), 228 (365 − $OP(OEt)_2^+$), 129 ($C_8H_{16}OH^+$); ^{1}H NMR ($CDCl_3$) δ 0.85 (3H, t, *J* = 6.8 Hz), 1.24−1.67 (19H, m), 2.81 (1H, ddd, *J* = 18.8, 10.2, and *8.6* Hz), 3.96−4.05 (1H, m), 4.07−4.22 (4H, m), 6.00 (1H, ddd, *J* = 15.8, 10.2, and 5.9 Hz), 6.51 (1H, dd, *J* = 15.8 and 4.9 Hz), 7.22−7.60 (5H, m); ^{13}C NMR ($CDCl_3$) δ 14.1, 16.4 (d, *J* = 4.9 Hz), 16.5 (d, *J* = 6.1 Hz), 22.6, 25.0, 29.3, 29.5, 31.8, 35.5 (d, *J* = 12.2 Hz), 49.7 (d, *J* = 134.3 Hz), 62.4 (d, *J* = 7.3 Hz), 62.7 (d, *J* = 7.3 Hz), 70.2 (d, *J* = 4.9 Hz), 121.8 (d, *J* = 11.0 Hz), 126.3, 127.8, 128.6, 134.6 (d, *J* = 13.4 Hz), 136.7. Anal. Calcd for $C_{21}H_{35}O_4P$: C, 65.95; H, 9.22. Found: C, 65.92; H, 9.22. (*erythro*-Isomer, minor): yellow oil; R_f = 0.37 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3418, 1598, 1229, 1028 cm^{-1}; MS *m*/*z* 365 (M^+ − OH), 250, 228 (365 − $OP(OEt)_2^+$), 129 ($C_8H_{16}OH^+$); ^{1}H NMR ($CDCl_3$) δ 0.86 (3H, t, *J* = 6.9 Hz), 1.20−1.60 (18H, m), 1.74 (1H, br), 2.81 (1H, ddd, *J* = 13.0, 10.0, and *1.5* Hz), 4.03−4.22 (5H, m), 6.35 (1H, ddd, *J* = 16.0, 10.0, and 6.2 Hz), 6.55 (1H, dd, *J* = 16.0 and 5.2 Hz), 7.23−7.42 (5H, m); ^{13}C NMR ($CDCl_3$) δ 14.1, 16.5 (d, *J* = 5.7 Hz), 22.6, 25.7, 29.2, 29.4, 31.8, 34.9 (d, *J* = 13.9 Hz), 47.9 (d, *J* = 136.2 Hz), 62.0 (d, *J* = 7.4 Hz), 63.2 (d, *J* = 7.4 Hz), 69.9 (d, *J* = 5.7 Hz), 119.7 (d, *J* = 9.0 Hz), 126.3, 127.8, 128.6, 136.0 (d, *J* = 14.8 Hz), 136.7.

Diethyl 5-Hydroxy-2(*E*)-dodecen-4-ylphosphonate (27). (*threo*-Isomer, major): colorless oil; R_f = 0.55 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3404, 1229, 1028 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.88 (3H, t, *J* = 6.9 Hz), 1.20−1.70 (18H, m), 1.73 (3H, t, *J* = 5.9 Hz), 2.58 (1H, dt, *J* = 18.6 and *9.3* Hz), 3.91−3.96 (2H, m), 4.06−4.23 (4H, m), 5.19−5.31 (1H, m), 5.61 (1H, ddd, *J* = 15.3, 6.9, and 4.9 Hz); ^{13}C NMR ($CDCl_3$) δ 14.0, 16.3 (d, *J* = 6.1 Hz), 16.4 (d, *J* = 6.1 Hz), 18.1 (d, *J* = 2.4 Hz), 22.6, 24.9, 29.3, 29.5, 31.8, 35.1 (d, *J* = 12.4 Hz), 49.1 (d, *J* = 134.3 Hz), 62.1 (d, *J* = 6.1 Hz), 62.4 (d, *J* = 7.3 Hz), 70.0 (d, *J* = 4.8 Hz), 122.8 (d, *J* = 11.0 Hz), 130.9 (d, *J* = 13.4 Hz); HRMS calcd for $C_{16}H_{32}O_3P$ (M^+ − OH) 303.2087, found 303.2114. Anal. Calcd for $C_{16}H_{33}O_4P$: C, 59.98; H, 10.38. Found: C, 59.95; H, 10.48. (*erythro*-Isomer, minor): colorless oil; R_f = 0.52 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3394, 1232, 1029 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.88 (3H, t, *J* = 6.9 Hz), 1.19−1.57 (18H, m), 1.75 (3H, t, *J* = 5.1 Hz), 2.57 (1H, ddd, *J* = 22.4, 9.2, and *1.8* Hz), 3.34 (1H, br s). 4.00−4.19 (5H, m), 5.49−5.73 (2H, m); ^{13}C NMR ($CDCl_3$) δ 14.1, 16.4 (d, *J* = 6.1 Hz), 18.2, 22.6, 25.7, 29.2, 29.4, 31.8, 34.6 (d, *J* = 13.4 Hz), 47.2 (d, *J* = 136.7 Hz), 61.8 (d, *J* = 7.3 Hz), 62.8 (d, *J* = 7.3 Hz), 69.8 (d, *J* = 4.9 Hz), 120.6 (d, *J* = 8.5 Hz), 132.2 (d, *J* = 4.7 Hz).

Diethyl 4-Hydroxy-3-methyl-1(*E*)-undecenylphosphonate (27′). Obtained as a mixture of two diastereomers (68/32): colorless oil; R_f = 0.33 (silica gel, hexane/EtOAc = 1/1); ^{1}H NMR ($CDCl_3$) δ (major isomer) 0.88 (3H, t, *J* = 6.6 Hz), 1.09 (3H, d, *J* = 6.6 Hz), 1.20−1.60 (18H, m), 1.70 (1H, br), 2.34−2.46 (1H, m), 3.48−3.62 (1H, m), 4.03−4.20 (4H, m), 5.70 (1H, dd, *J* = 20.9 and 17.4 Hz), 6.78 (1H, ddd, *J* = 22.3, 17.4, and 7.6 Hz), (minor isomer) 1.08 (d, *J* = 6.6 Hz); ^{13}C NMR ($CDCl_3$) δ (major isomer) 14.0, 15.5, 16.3 (d, *J* = 6.1 Hz), 22.6, 25.7, 29.2, 29.5, 31.8, 34.5, 44.4 (d, *J* = 10.7 Hz), 61.7 (d, *J* = 6.1 Hz), 74.6, 117.8 (d, *J* = 186.8 Hz), 154.9 (d, *J* = 4.9 Hz), (minor isomer) 13.5, 14.2, 16.3 (d, *J* = 6.1 Hz), 23.3, 24.7, 26.0, 29.7, 34.4, 36.6, 44.1 (d, *J* = 8.3 Hz), 61.7 (d, *J* = 6.1 Hz), 74.2, 117.1 (d, *J* = 186.8 Hz), 155.7 (d, *J* = 4.9 Hz).

Diethyl 3,7-Dimethyl-1-(1′-hydroxycyclohexyl)-2,6-octadienylphosphonate (28). Obtained as a mixture of (*E*) and (*Z*)-isomer (61:39): yellow oil; R_f = 0.51 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3423, 1262, 1028 cm^{-1}; MS *m*/*z* 357 (M^+ − Me), 275, 206, 151; ^{1}H NMR ($CDCl_3$) δ 1.29 (3H, t, *J* = 6.8 Hz), 1.32 (3H, t, *J* = 6.8 Hz), 1.37−1.81 (20H, m), 2.00−2.20 (4H, m), 2.93 (0.6H, dd, *J* = 21.3 and 11.1 Hz, major), 2.96 (0.4H, dd, *J* = 21.4 and 11.2 Hz, minor), 4.00−4.35 (4H, m), 5.02−5.16 (1H, m), 5.16−5.28 (1H, m); ^{13}C NMR ($CDCl_3$) (clearly assignable peaks) δ 48.1 (d, *J* = 131.8 Hz, minor) and 48.4 (d, *J* = 131.8 Hz, major), 72.5 (d, *J* = 4.9 Hz, minor) and 72.7 (d, *J* = 4.9 Hz, major), 116.87 (d, *J* = 9.7 Hz, major) and 116.93 (d, *J* = 9.7 Hz, minor), 123.9 (major and minor), 131.6 (major) and 131.8 (minor), 140.4 (d, *J* = 13.5 Hz, major) and 140.5 (d, *J* = 13.4 Hz, minor). Anal. Calcd for $C_{20}H_{37}O_4P$: C, 64.49; H, 10.01. Found: C, 64.73; H, 9.89.

Diethyl 2,6-Dimethyl-9-hydroxy-2,6-hexadecadien-8-ylphosphonate (29). (*threo*-Isomer): obtained as a mixture of (*E*) and (*Z*)-isomer (78:22); yellow oil; R_f = 0.40 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3384, 1229, 1029 cm^{-1}; MS *m*/*z* 402 (M^+), 273 ($M^+ - C_8H_{16}OH$), 232, 206; ^{1}H NMR ($CDCl_3$) (major isomer) δ 0.87 (3H, t, *J* = 6.9 Hz), 1.26−1.78 (28H, m), 2.06−2.14 (4H, m), 2.86 (1H, dt, *J* = 19.0 and *9.6* Hz), 3.78−3.93 (1H, m), 4.08−4.19 (4H, m), 4.96 (1H, dd, *J* = 10.4 and

4.8 Hz), 5.02−5.12 (1H, m); ^{13}C NMR ($CDCl_3$) (clearly assignable peaks) δ 42.7 (d, J = 135.4 Hz, minor) and 44.6 (d, J = 134.3 Hz, major), 70.5 (d, J = 4.9 Hz, major) and 70.8 (d, J = 3.6 Hz, minor), 116.5 (d, J = 11.0 Hz, major) and 116.8 (d, J = 9.8 Hz, minor), 123.8 (major and minor), 131.7 (major) and 132.0 (minor), 140.0 (d, J = 13.4 Hz, major) and 141.5 (d, J = 13.4 Hz, minor). Anal. Calcd for $C_{22}H_{43}O_4P$: C, 65.64; H, 10.77. Found: C, 65.63; H, 10.75. (*erythro*-Isomer): obtained as a mixture of (*E*) and (*Z*)-isomer (74:26); yellow oil; R_f = 0.39 (silica gel, hexane/EtOAc = 1/1); ^{1}H NMR ($CDCl_3$) (major isomer) δ 0.87 (3H, t, J = 6.9 Hz), 1.26−1.81 (28H, m), 2.05−2.15 (4H, m), 2.83 (1H, ddd, J = 23.1, 10.7 and *2.1* Hz), 3.99−4.17 (5H, m), 5.03−5.15 (1H, m), 5.35 (1H, dd, J = 10.4 and 4.6 Hz); ^{13}C NMR ($CDCl_3$) (clearly assignable peaks) δ 42.7 (d, J = 129.3 Hz, minor) and 42.8 (d, J = 136.7 Hz, major), 70.0 (d, J = 4.9 Hz, major) and 70.5 (d, J = 4.9 Hz, minor), 113.9 (d, J = 8.5 Hz, major) and 114.2 (d, J = 8.6 Hz, minor), 123.8 (major and minor), 131.7 (major) and 131.9 (minor), 141.5 (d, J = 13.4 Hz, major) and 141.8 (d, J = 13.4 Hz, minor).

Diethyl 3,7-Dimethyl-1-(1′-hydroxycyclohexyl)-6-octenylphosphonate (30). Obtained as a mixture of two diastereoisomers (56:44): colorless oil; R_f = 0.40 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3398, 1234, 1026 cm^{-1}; ^{1}H NMR ($CDCl_3$) (major isomer) δ 0.83 (3H, d, J = 6.3 Hz), 0.94−2.06 (18H, m), 1.26 (6H, t, J = 6.3 Hz), 1.54 (3H, s), 1.61 (3H, s), 3.92−4.15 (4H, m), 4.37 (1H, br s), 4.96−5.07 (1H, m), (minor isomer) 0.80 (d, J = 6.6 Hz), 1.25 (t, J = 6.3 Hz), 4.45 (br s); ^{13}C NMR ($CDCl_3$) (clearly assignable peaks) δ 16.4 (d, J = 6.1 Hz, major and minor), 46.3 (d, J = 130.6 Hz, major) and 46.5 (d, J = 130.7 Hz, minor), 61.36, 61.45, and 61.6 (three d, J = 7.3 Hz, major and minor), 72.6 (d, J = 4.8 Hz, minor) and 72.8 (d, J = 3.7 Hz, major), 124.6 (major) and 124.7 (minor), 131.2 (minor) and 131.3 (major). Anal. Calcd for $C_{20}H_{39}O_4P$: C, 64.14; H, 10.50. Found: C, 64.31; H, 10.45.

Diethyl 1-(1′-Cyclohexenyl)octylphosphonate (31′). Colorless oil; IR (neat) 1653, 1248, 1028 cm^{-1}; MS m/z 330 (M^+), 246, 233, 135, 94; ^{1}H NMR ($CDCl_3$) δ 0.88 (3H, t, J = 6.6 Hz), 1.14−1.40 (16H, m), 1.53−1.79 (6H, m), 1.95−2.18 (4H, m), 2.36 (1H, ddd, J = 22.8, 9.6, and 5.6 Hz), 4.00−4.18 (4H, m), 5.59−5.68 (1H, m); ^{13}C NMR ($CDCl_3$) δ 14.1, 16.4 (d, J = 6.1 Hz), 16.5 (d, J = 4.9 Hz), 22.3, 22.6, 23.0, 25.5, 27.0, 27.1, 27.4 (d, J = 4.9 Hz), 27.6, 29.1 (d, J = 9.8 Hz), 31.8, 45.9 (d, J = 135.5 Hz), 61.4 (d, J = 7.3 Hz), 62.1 (d, J = 7.3 Hz), 126.5 (d, J = 12.2 Hz) 132.2 (d, J = 8.5 Hz). Anal. Calcd for $C_{18}H_{35}O_3P$: C, 65.43; H, 10.68. Found: C, 65.71; H, 10.53.

Diethyl 1-(1′-Hydroxycyclohexyl)-2(*E*)-butenylphosphonate (32). Colorless oil; R_f = 0.31 (silica gel, hexane/EtOAc = 1/1); IR (neat) 3425, 1223, 1024 cm^{-1}; MS m/z 193, 165, 137 $(OP(OEt)_2^+)$; ^{1}H NMR ($CDCl_3$) δ 1.12−1.78 (14H, m), 1.30 (3H, t, J = 6.9 Hz), 1.32 (3H, t, J = 6.9 Hz), 2.62 (1H, dd, J = 20.6 and 10.1 Hz), 4.05−4.16 (4H, m), 5.35−5.65 (2H, m); ^{13}C NMR ($CDCl_3$) δ 16.3, (d, J = 6.1 Hz), 18.2, 21.6, 21.8, 25.4, 34.8 (d, J = 7.3 Hz), 37.3 (d, J = 9.8 Hz), 53.3 (d, J = 130.6 Hz), 61.8 (d, J = 7.3 Hz), 62.3 (d, J = 7.3 Hz), 72.0 (d, J = 3.7 Hz), 123.2 (d, J = 9.8 Hz) 131.3 (d, J = 7.3 Hz). Anal. Calcd for $C_{14}H_{27}O_4P$: C, 57.92; H, 9.37. Found: C, 58.23; H, 9.28.

Conversion of β-Hydroxyphosphonates 25 and 26 to Olefins 33 and 34. Pure *threo*- or *erythro*-β-hydroxyphosphonate (0.5 mmol) in THF (5 mL) was added to a suspension of NaH (15 mg, 0.6 mmol) in THF (5 mL) at room temperature or −15 °C, and the mixture was stirred for an appropriate time (eq 6) with monitoring by GC. After usual workup, the residue was chromatographed on silica gel with hexane eluent to give **33** (64% from *threo*-**25** and 68% from *erythro*-**25**) or **34** (75% from *threo*-**26** and 68% from *erythro*-**26**) as a mixture of (*E*,*E*) and (*E*,*Z*)-isomers. The ratio of the two isomers was determined by GC of the crude reaction mixture.

General Procedure for the One-Pot Coupling of Acylphosphonates 1 with Two Carbonyl Compounds. Method A (one-step reaction): SmI_2 (0.1 M in THF, 20 mL) was slowly added to a solution of acylphosphonate **1** (0.5 mmol), aldehyde (1 mmol), and the second aldehyde or ketone (0.4 mmol) in THF (3 mL)−HMPA (1 mL) over 1 h at 0 °C and stirring was continued for additional 1 h at 0 °C. The reaction was quenched with hydrochloric acid (2 M, 10 mL), and an internal standard such as tridecane was added to the mixture. Then, the reaction mixture was extracted with ether, washed with sodium hydrogensulfite solution and brine, dried over $MgSO_4$, and concentrated in vacuo. The products were isolated by column chromatography on silica gel with hexanes/EtOAc eluent. Method B (two-step reaction): SmI_2 (0.1 M in THF, 5 mL) was slowly added to a solution of acylphosphonate **1** (0.5 mmol) and aldehyde (1 mmol) in THF (3 mL)−HMPA (1 mL) over 15 min at 0 °C, and the mixture was stirred for additional 45 min at 0 °C. After addition of the second aldehyde or ketone (0.4 mmol), SmI_2 (15 mL, 1.5 mmol) was added over 15 min to the mixture at 0 °C, and then stirring was continued for 45 min at room temperature. The mixture was worked up similarly as above.

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Supporting Information Available: Characterization data (IR, MS, ^{1}H and ^{13}C NMR spectra and elemental analyses) of compounds **2**−**14**, **17**−**21**, **33**, and **34**. This material is available free of charge via the Internet at http://pubs.asc.org.

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