Facile Synthesis of 1,4-Diketones via Palladium Complex Catalyzed Isomerization of Alkynediols

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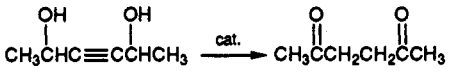
Alkynediols isomerized under the catalysis of $Pd_2(dba)_3{\cdot}CHCl_3$ + 2*n*-Bu_3P in acetonitrile at 80 °C to give 1,4-diketones in high yields. This experimentally simple and economically synthetic method is illustrated with examples including substituents such as alkyl, alkenyl, and aryl groups. The order of reactivity of the substituents in this reaction is aryl ≥ alkenyl > alkyl. Alkenyl-substituted alkynediols chemoselectively isomerized to the corresponding α,β-unsaturated 1,4-diketones. The usefulness of this novel method is exemplified by the synthesis of dihydrojasmone.

Introduction

1,4-Diketones are valuable precursors for the synthesis of cyclopentenones and five-membered heterocycles.[1] 1,4-Diketones have been prepared in many ways;[2-8] most of them follow lengthy procedures and require multistep preparation of a special reagent. Therefore, simpler methods of synthesis of 1,4-diketones from easily accessible starting materials under mild conditions are of great interest. Although intramolecular hydrogen-transfer reaction of olefins catalyzed by transition-metal complexes has attracted much attention in recent years,[9] intramolecular hydrogen-transfer reactions of carbon–carbon triple bonds are rare.[10] We have studied the transition-metal-catalyzed isomerization of acetylenic derivatives, which has been proved to be an efficient procedure in organic synthesis.[10,11]

Table I. Isomerization of 3-Hexane-2,5-diol (1a) to 2,5-Hexanedione (2a) under the Catalysis of Transition-Metal Complexes[a]



1a 2a

entry	catalyst	L	L/cat.	solvent	time (h)	yield (%)[b]
1	$IrH_5(i\text{-}Pr_3P)_2$		0	toluene	40	70
2	$RhH(Ph_3P)_4$	*n*-Bu_3P	2	MeCN	70	0
3	$RuCl_2(Ph_3P)_3$	*n*-Bu_3P	2	MeCN	70	0
4	$Pd(OAc)_2$	*n*-Bu_3P	2	MeCN	70	58
5	$Pd_2(dba)_3{\cdot}CHCl_3$	*n*-Bu_3P	2	MeCN	70	84
6	$Pd_2(dba)_3{\cdot}CHCl_3$	*n*-Bu_3P	2	$CHCl_3$	70	76
7	$Pd_2(dba)_3{\cdot}CHCl_3$	*n*-Bu_3P	2	$C_6H_5CH_3$	70	44
8	$Pd_2(dba)_3{\cdot}CHCl_3$	*n*-Bu_3P	2	THF	70	0
9	$Pd_2(dba)_3{\cdot}CHCl_3$	*n*-Bu_3P	2	DMF[c]	70	0
10	$Pd_2(dba)_3{\cdot}CHCl_3$	*n*-Bu_3P	2	dioxane	70	0

[a] Reaction condition: 1a (2.0 mmol), catalyst, $IrH_5(i\text{-}Pr_3P)_2$ (0.04 mmol), $RhH(Ph_3P)_4$, $RuCl_2(Ph_3P)_3$, or $Pd_2(dba)_3{\cdot}CHCl_3$ (0.1 mmol), and solvent (10 mL) were heated at reflux. [b] Isolated yield. The products were confirmed by ^1H NMR, mass, and IR spectra. [c] The reaction was carried out at 110 °C.

Table II. Isomerization of 3-Hexyne-2,5-diol (1a) to 2,5-Hexanedione (2a) under the Catalysis of $Pd_2(dba)_3{\cdot}CHCl_3$[a]

entry	L	L/cat.	yield (%)[b]
1	0	0	55
2	*n*-Bu_3P	2	84
3	*n*-Bu_3P	4	62
4	Ph_3P	2	23
5	dppe	2	17

[a] Reaction condition: 1a (2.0 mmol) and $Pd_2(dba)_3{\cdot}CHCl_3$ (0.1 mmol) in MeCN (10 mL) were heated at reflux for 70 h. [b] Isolated yield. The products were confirmed by ^1H NMR, mass, and IR spectra.

In an early communication,[10a] we described the conversion of 3-hexyne-2,5-diol (**1a**) to 2,5-hexanedione (**2a**) using $IrH_5(i\text{-}Pr_3P)_2$ as catalyst. The simplicity of this new methodology stimulated us to study the isomerization in detail. We wish to report here that 1,4-diketones can be prepared by the isomerization of ynediols in high yields using $Pd_2(dba)_3{\cdot}CHCl_3$ + 2*n*-Bu_3P as the catalyst.

Results and Discussion

Catalysts. Various transition-metal complexes were examined as catalysts for the isomerization of **1a** (Table I). Complexes $IrH_5(i\text{-}Pr_3P)_2$ and $Pd_2(dba)_3{\cdot}CHCl_3$ + 2*n*-

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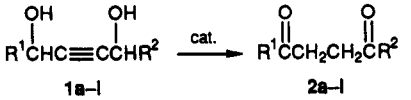
Table III. Isomerization of Substituted Alkynediols to Substituted 1,4-Diketones under the Catalysis of Transition-Metal Complexes



1a–l 2a–l

entry	R^1	R^2	no.	cat.[a]	time (h)	product[b]	yield (%)[c]
1	CH_3	CH_3	1a	A	40	2a	70
2			1a	C	70	2a	58
3			1a	B	70	2a	84
4	C_2H_5	C_2H_5	1b	A	70	2b	81
5			1b	B	70	2b	72
6	C_2H_5	C_7H_{15}	1c	A	70	2c	80
7			1c	B	70	2c	68
8	CH_3	C_6H_{13}	1d	B	70	2d	87
9	C_6H_5	C_6H_5	1e	B	15	2e	96
10			1e	C	15	2e	75
11			1e	D	60	2e	91
12	C_6H_5	CH_3	1f	B	20	2f	98
13	p-$CH_3OC_6H_4$	CH_3	1g	B	20	2g	97
14	p-FC_6H_4	CH_3	1h	B	25	2h	94
15	(*E*)-CH_3CH=CH	(*E*)-CH_3CH=CH	1i	B	30	2i	72
16	(*E*)-C_6H_5CH=CH	(*E*)-C_6H_5CH=CH	1j	B	20	2j	93
17	(*E*)-C_6H_5CH=CH	CH_3	1k	B	40	2k	82
18	(*E*)-CH_3CH=CH	C_4H_9	1l	B	50	2l	86

[a] A: 1 (2 mmol) and $IrH_5(i\text{-}Pr_3P)_2$ (0.04 mmol) in toluene (10 mL) were heated at reflux. B: 1 (2 mmol), $Pd_2(dba)_3$·$CHCl_3$ (0.1 mmol), n-Bu_3P (0.2 mmol), and MeCN (10 mL) were heated at reflux. C: 1 (2 mmol), $Pd(OAc)_2$ (0.1 mmol), n-Bu_3P (0.2 mmol), and MeCN (10 mL) were heated at reflux. D: Same as B, but Ph_3P (0.1 mmol) was used instead of n-Bu_3P. [b] The products were characterized with ^1H NMR, mass, and IR spectra. [c] Isolated yield.

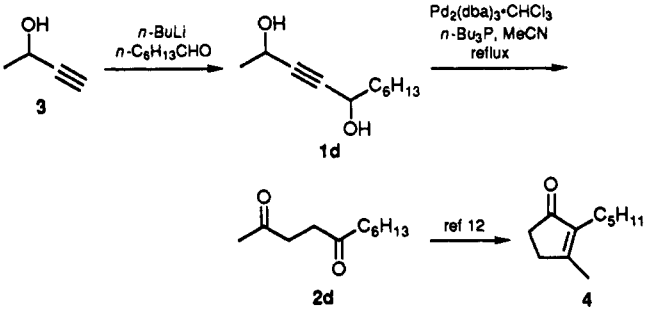
Bu_3P show high catalytic reactivity. Although $RuCl_2(Ph_3P)_3$ and $RhH(Ph_3P)_4$ show high catalytic reactivity in toluene,[10b,11d] they are inactive in acetonitrile, possibly because of lower reaction temperature.

Solvents. While dioxane, THF, and DMF are not good solvents for this reaction, acetonitrile, toluene, and chloroform are suitable solvents. Acetonitrile was chosen as the solvent for studying this reaction because of its milder reaction temperature (Table I).

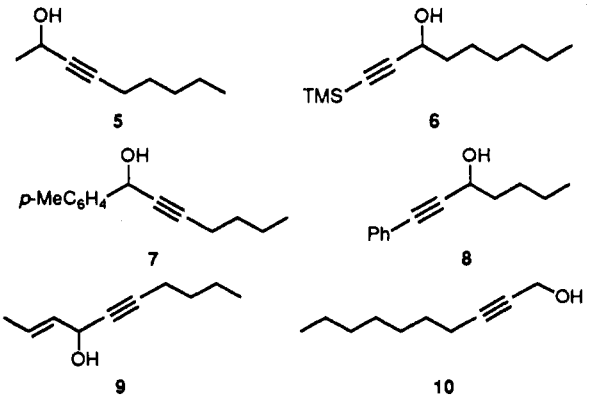
Effect of Ligand. Table II shows that phosphine ligands influence significantly the activity of the catalysts. When 5 mol % of $Pd_2(dba)_3$·$CHCl_3$ and 10 mol % of n-Bu_3P as catalyst in acetonitrile were reacted at reflux for 70 h, **1a** isomerized to **2a** in the highest yield (entry 7, Table II).

Catalytic Isomerization of Substituted Alkynediols to Substituted 1,4-Diketones. Three catalyts were examined for their capacity to isomerize alkynediols **1a–l** to the corresponding 1,4-diketones **2a–l**. With 2 mol % of $IrH_5(i\text{-}Pr_3P)_2$ in toluene at reflux (entries 1, 4, and 6, Table III), or under 5 mol % of $Pd_2(dba)_3$·$CHCl_3$ + 10 mol % of n-Bu_3P in acetonitrile at reflux (entries 3, 5, 7–9, and 12–18, Table III), alkynediols isomerized to 1,4-diketones in high yields. Considering the easy accessibility and stability of the catalyst, the mild reaction conditions, and the simple procedure, we chose $Pd_2(dba)_3$·$CHCl_3$ + 2n-Bu_3P as the catalytic system. The aryl-substituted alkynediols (entries 9–14, Table III) were more easily isomerized to corresponding 1,4-diketones than alkyl-substituted ones. Alkenyl-substituted alkynediols **1i–l** isomerized to the corresponding α,β-unsaturated 1,4-diketones **2i–l**. It is surprising that only isomerization of the triple bond occurred, while the alkenyl group remained intact and the configuration of the double bond was preserved. Dialkenyl-substituted alkynediols (entries 15 and 16) isomerized faster than alkenyl- and alkyl-substituted alkynediols (entries 17 and 18). The order of the reactivity of the substituents in the isomerization reaction is aryl ≥ alkenyl > alkyl. It is in parallel with the order of the acidity of the hydrogen atom on the carbon atom at which the hydroxy group is linked. The starting materials of this reaction are easily prepared by known methods from acetylene carbanions and carbonyl compounds in large scale.

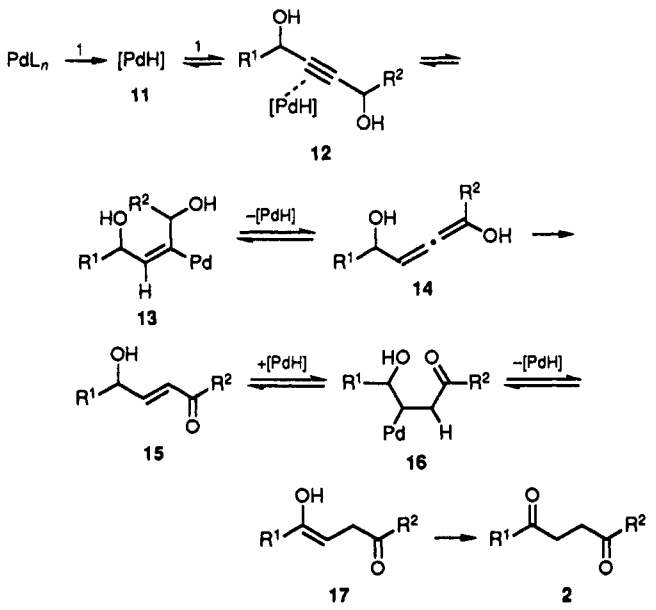
2,5-Undecanedione (**2d**), a precursor of synthesis of dihydrojasmone, could be synthesized from 3-butyn-2-ol (**3**) by using our method.



Although palladium-catalyzed isomerization of alkynediols gave satisfactory results, this catalytic system failed to catalyze the isomerization of alkynols, such as **5–10**, to the corresponding α,β-unsaturated ketones or aldehydes under the same conditions.



Scheme I[a,b]



[a] [PdH] = L_mPdH. [b] L_mPdH represents the active species containing a Pd-H bond. It is still not certain whether L represents dba, *n*-Bu_3P, solvent, or alkoxy group from the reaction of Pd(0) with alkynediol.

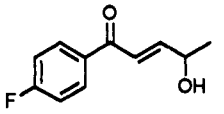
Mechanism. In our early reports on the isomerization of alkyne derivatives catalyzed by ruthenium and iridium complexes,[13] we proposed a mechanism consisting of repeated hydrometalation of the carbon–carbon unsaturated bonds. In discussions of the hydrogenation of alkenes over transition-metal complexes using alcohols as hydrogen donors, it is generally suggested[14] that this reaction occurs via initial formation of a metal hydride species by the oxidative addition of alcohols to the transition-metal complexes, followed by transfer of the hydride to the alkenes.[15,16] In our case, the [Pd–H] species (11) may be also generated from the oxidative addition of the hydroxy group of the alkynediol to the zero-valent palladium of $Pd_2(dba)_3$·$CHCl_3$. By hydropalladation, the alkenyl palladium 13 is formed. The allene intermediate 14 occurs by dehydropalladation, which isomerizes to γ-hydroxy-α,β-unsaturated ketone 15. Again, by hydropalladation and dehydropalladation of the allylic alcohol 15, the substituted 1,4-diketone 2 is finally formed (Scheme I). Although Alper[9d] reported a π-metal complex mechanism of allylic alcohols to ketones catalyzed by a rhodium complex, the preservation of the C=C bond in the isomerization of the alkenyl-substituted alkynediol rules out this possibility.

The oxidative addition of alcohols to transition-metal complexes is well known,[9b,17] but few examples of the oxidative addition of alcohols to palladium complexes have been reported.[14] Pasquali[18] reported the oxidative addition of phenols to $Pd(Cy_3P)_2$ only because of the weak acidity of phenol. Yamamoto[19] reported that only alcohols of sufficient acidity could react with PdR_2L_2. In our catalytic system, the first important step may be the in situ formation of [Pd–H] species from Pd(0) and alkynediols. The failure of the isomerization of the alkynols to the corresponding enones under the same conditions may be due to the difficulty of forming the [Pd–H] species, which is consistent with both Pasquali's and Yamamoto's results that no reactions occurred when aliphatic alcohols were employed.

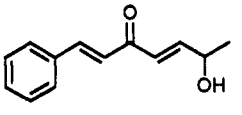
Evidence for the formation of a [Pd–H] species by oxidative addition of alkynediols with Pd(0) was obtained by monitoring the reaction with ^1H NMR spectroscopy. For the system containing **1a**, 20 mol % of $Pd_2(dba)_3$·$CHCl_3$, and 40 mol % of *n*-Bu_3P, three signals (δ = −12.9, −16.2, −18.7) appeared after the solution was allowed to stand at room temperature for 8 h. The chemical shifts of signals at characteristic high field indicate the presence of a [Pd–H] species.[20] The characteristic signals for the [Pd–H] species did not appear for alkynol **6** under the same conditions, which is consistent with the failure of isomerization.

The easy oxidative addition of alkynediols with Pd(0) may be attributed to chelation of the alkynediol with palladium. The coordination of oxygen atom to Pd(0) may assist the oxidative addition reaction of the other O–H bond to Pd(0). That the isomerization reaction occurs only at the triple bond of alkenyl-substituted alkynediols (entries 15–18) may be explained by this chelation.

Table III shows that the reaction of **1h** (entry 14) was complete after 25 h. If the reaction was interrupted after 10 h, **15h** and **2h** were isolated in 10% and 23% yields, respectively. Similarly, the reaction of **1k** (entry 17) was stopped after 20 h. **2k** and **15k** were isolated in 54% and 23% yields, respectively. Experiments showed that **15h** and **15k** did transform into **2h** and **2k** in 82% and 75% yields, respectively, on further reaction. The isolation of **15h** and **15k** in the intermediate stage of the reaction supports the mechanism shown in Scheme I. Thus, **15** is an intermediate in the reaction and the hydrogen-transfer reaction occurs first between the allylic or benzylic hydroxy group and the triple bond.



15h



15k

Experimental Section

All reactions were carried out under purified Ar. Acetonitrile was distilled from P_2O_5 under N_2. Toluene was distilled from sodium and benzophenone under N_2. ^1H NMR spectra were recorded in $CDCl_3$ at 60 MHz unless specified otherwise.

Materials. Complexes $IrH_5(i\text{-}Pr_3P)_2$[21] $Pd_2(dba)_3$·$CHCl_3$,[22] $RuCl_2(Ph_3P)_3$,[23] and $RhH(Ph_3P)_4$[24] were prepared according to reported methods.

Alkynediols were prepared by the reaction of acetylene dimagnesium bromide or dilithium acetylide with the corresponding aldehydes or by the reaction of alkynylmagnesium bromide or lithium acetylide with the corresponding aldehydes.[25] The

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mixtures of diastereoisomers were used directly without separation.

4-Octyne-1,4-diol (1b): yield 51%; bp 92–95 °C (1 mmHg) (lit.[27] bp 90–95 °C (0.05 Torr)).

4-Tridecyne-3,7-diol (1c): yield 58%; bp 116–119 °C (0.5 mmHg); IR (neat) 3335, 2250 cm^{-1}; ^1H NMR (CCl_4) δ 4.2 (m, 2 H), 3.9 (s, 2 H), 1.3 (m, 14 H), 0.9 (t, J = 7 Hz, 6 H); MS m/e 212 (M^+), 211, 176, 119, 95, 57, 43. Anal. Calcd for $C_{13}H_{24}O_2$: C, 73.58; H, 11.32. Found: C, 73.36; H, 11.31.

3-Undecyne-2,5-diol (1d): yield 83%; ot (oven temperature) 130 °C (1 mmHg); IR (neat) 3300, 2200 cm^{-1}; ^1H NMR (CCl_4) δ 4.4–4.2 (m, 4 H), 1.4–0.8 (m, 16 H); MS m/e 184 (M^+), 183, 167, 149, 43. Anal. Calcd for $C_{11}H_{20}O_2$: C, 71.70; H, 10.94. Found: C, 71.62; H, 11.12.

1,4-Diphenyl-2-butyne-1,4-diol (1e): yield 59%; mp 130–132 °C (lit.[26] mp 129–130 °C).

1-Phenyl-2-pentyne-1,4-diol (1f): yield 57%; ot 145 °C (0.5 mmHg); IR (Nujol) 3250, 2300, 1600, 1500, 750, 700 cm^{-1}; ^1H NMR δ 7.7–7.4 (m, 5 H), 5.5 (s, 1 H), 4.6 (q, J = 6 Hz, 1 H), 3.2 (s, 2 H), 1.4 (d, J = 6 Hz, 3 H); MS m/e 176 (M^+), 158, 129, 105, 91, 77, 43. Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.73; H, 7.08.

1-(*p*-Methoxyphenyl)-2-pentyne-1,4-diol (1g): yield 55%; ot 155–160 °C (0.5 mmHg); IR (Nujol) 3300, 2050, 1610, 1590, 1510, 1250, 830 cm^{-1}; ^1H NMR δ 7.5 (d, J = 8 Hz, 2 H), 6.8 (d, J = 8 Hz, 2 H), 5.4 (s, 1 H), 4.5 (q, J = 6 Hz, 1 H), 3.8 (s, 3 H), 2.7 (m, 2 H), 1.4 (d, J = 6 Hz, 3 H); MS m/e 206 (M^+), 189, 159, 109, 77, 43. Anal. Calcd for $C_{12}H_{14}O_3$: C, 69.90; H, 6.80. Found: C, 69.56; H, 7.03.

1-(*p*-Fluorophenyl)-2-pentyne-1,4-diol (1h): yield 86%; ot 145–150 °C (0.5 mmHg); IR (Nujol) 3300, 2200, 1600, 1500, 840 cm^{-1}; ^1H NMR δ 7.4–7.3 (m, 2 H), 6.9–6.7 (m, 2 H), 5.2 (s, 1 H), 4.3–4.2 (m, 3 H), 1.2 (d, J = 6 Hz, 3 H); ^{19}F NMR (60 MHz/$CDCl_3$/CF_3CO_2H) δ 37; MS m/e 194 (M^+), 176, 149, 97, 69, 43. Anal. Calcd for $C_{11}H_{11}FO_2$: C, 68.02; H, 5.67; F, 9.79. Found: C, 67.67; H, 5.77; F, 9.68.

(2*E*,8*E*)-Deca-2,8-dien-5-yne-4,7-diol (1i): yield 91%; ot 150–154 °C (1 mmHg); IR (neat) 3300, 3030, 2200, 1670, 960 cm^{-1}; ^1H NMR (90 MHz) δ 5.8 (dq, J = 18, 4 Hz, 2 H), 5.6 (dd, J = 18, 4 Hz, 2 H), 4.9 (d, J = 4 Hz, 2 H), 2.8 (s, 2 H), 1.7 (d, J = 4 Hz, 6 H); MS m/e 166 (M^+), 165, 132, 121, 69, 55, 43. Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.25; H, 8.49. Found: C, 72.56; H, 8.43.

(1*E*,7*E*)-1,7-Diphenylocta-1,7-dien-4-yne-3,6-diol (1j): yield 83%; mp 105–107 °C; IR (Nujol) 3300, 3030, 2300, 1640, 1600, 1580, 1500, 960 cm^{-1}; ^1H NMR (90 MHz/CD_3COCD_3) δ 7.4–7.0 (m 10 H), 6.6 (d, J = 16 Hz, 2 H), 6.3 (dd, J = 16, 5 Hz, 2 H), 5.1 (d, J = 5 Hz, 2 H), 3.1 (s, 2 H); MS m/e 290 (M^+), 272, 199, 186, 169, 105, 91, 77. Anal. Calcd for $C_{20}H_{18}O_2$: C, 82.73; H, 6.25. Found: C, 82.50; H, 6.35.

(1*E*)-1-Phenyl-1-hepten-4-yne-3,6-diol (1k): yield 50%; ot 160 °C (1 mmHg); IR (Nujol) 3400, 3050, 2300, 1640, 1600, 1580, 1500 cm^{-1}; ^1H NMR (90 MHz) δ 7.7 (m, 5 H), 7.1 (d, J = 18 Hz, 1 H), 6.6 (dd, J = 18, 5 Hz, 1 H), 5.4 (d, J = 5 Hz, 1 H), 4.9 (q, J = 6 Hz, 1 H), 3.5 (m, 2 H), 1.3 (d, J = 6 Hz, 3 H); MS m/e 202 (M^+), 185, 167, 159, 141, 115, 105, 91, 77, 43. Anal. Calcd for $C_{11}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 77.08; H, 7.04.

(2*E*)-2-Undecen-5-yne-4,7-diol (1l): yield 95%; ot 148–152 °C (1 mmHg); IR (neat) 3300, 3050, 1640 cm^{-1}; ^1H NMR δ 5.8 (dq, J = 16, 4 Hz, 1 H), 5.5 (dd, J = 16, 4 Hz, 1 H), 4.8 (d, J = 4 Hz, 1 H), 4.4–3.6 (m, 3 H), 1.7 (d, J = 4 Hz, 3 H), 1.5–0.9 (m, 9 H); MS m/e 182 (M^+), 181, 164, 147, 123, 107, 95, 85, 69, 57, 55, 43. Anal. Calcd for $C_{11}H_{18}O_2$: C, 72,49; H, 9.95. Found: C, 72.16; H, 9.85.

Catalytic Activity of Various Metal Complexes and Effect of Solvents. Under Ar, a mixture of **1a** (228 mg, 2.0 mmol), catalyst (0.1 mmol), n-Bu_3P (40 mg, 0.2 mmol), and solvent (10 mL) was placed in a Schlenk tube and heated at 80 °C for 70 h. The product **2a** was purified by Kugelrohr distillation under reduced pressure (Table I).

Effect of Phosphine Ligands. A mixture of **1a** (228 mg, 2.0 mmol), $Pd_2(dba)_3$·$CHCl_3$ (52 mg, 0.1 mmol), ligand, and acetonitrile (10 mL) was heated at 80 °C for 70 h. The product **2a** was purified by Kugelrohr distillation under reduced pressure (Table II).

Typical Procedure for the Preparation of 1,4-Diketones by the Isomerization of Alkynediols Catalyzed by $IrH_5(i\text{-}Pr_3P)_2$. A mixture of **1a** (228 mg, 2 mmol), $IrH_5(i\text{-}Pr_3P)_2$ (41 mg, 0.04 mmol), and toluene (10 mL) was heated in a Schlenk tube at 110 °C for 40 h. After cooling to rt and removal of the solvent, the red residue was purified by Kugelrohr distillation under reduced pressure to yield 2,5-hexanedione (**2a**): ot 90 °C (2 mmHg) (lit.[27] bp 191 °C (750 mmHg)); IR (neat) 2960, 1720 cm^{-1}; ^1H NMR (CCl_4) δ 2.3 (s, 4 H), 2.1 (s, 6 H); MS m/e 114 (M^+), 99, 71, 43.

Compounds **2b** and **2c** were prepared similarly.

3,6-Octanedione (2b): ot 125–130 °C (3 mmHg) (lit.[28] bp 45–50 °C (0.25 Torr)); IR (neat) 1715 cm^{-1}; ^1H NMR (CCl_4) δ 2.45 (s, 4 H), 2.3 (q, J = 6 Hz, 4 H), 1.00 (t, J = 6 Hz, 6 H); MS m/e 142 (M^+), 113, 95, 57.

3,6-Tridecanedione (2c): ot 130–134 °C (2 mmHg); IR (neat) 1720 cm^{-1}; ^1H NMR (CCl_4) δ 2.6 (m, 4 H), 2.4 (m, 4 H), 1.5–0.9 (m, 16 H); MS m/e 212 (M^+), 141, 122, 97, 79, 69, 57, 43. Anal. Calcd for $C_{13}H_{24}O_2$: C, 73.58; H, 11.32. Found: C, 73.29; H, 11.24.

Typical Procedure for the Preparation of 1,4-Diketones by the Isomerization of Alkynediols Catalyzed by Palladium Complexes. A mixture of **1a** (228 mg, 2 mmol), $Pd_2(dba)_3$·$CHCl_3$ (52 mg, 0.1 mmol), n-Bu_3P (40 mg, 0.2 mmol), and acetonitrile (10 mL) was placed in a Schlenk tube and heated at 80 °C for 70 h. The reaction was monitored with TLC (petroleum ether:ethyl acetate = 10:4). After cooling to rt and removal of solvent, the product **2a** was purified by Kugelrohr distillation under reduced pressure.

The following compounds were prepared similarly and purified by Kugelrohr distillation or by column chromatography on silica gel.

2,5-Undecanedione (2d): bp 94–98 °C (1 mmHg) (lit.[29] bp 75–77 °C (0.5 mmHg)); IR (neat) 1720 cm^{-1}; ^1H NMR (CCl_4) δ 2.5 (m, 4 H), 2.3–2.0 (m, 5 H), 1.2–0.9 (m, 11 H); MS m/e 184 (M^+), 166, 114, 99, 95, 71, 55, 43.

1,4-Diphenyl-1,4-pentanedione (2e): mp 141–142 °C (lit.[30] mp 143–144 °C); IR (Nujol) 1680, 1600, 1580, 1500 cm^{-1}; ^1H NMR (CCl_4) δ 7.8–7.6 (dd, J = 8, 2 Hz, 4 H), 7.3 (m, 6 H), 3.0 (s, 4 H); MS m/e 238 (M^+), 133, 105, 77, 55, 51.

1-Phenyl-1,4-pentanedione (2f): bp 100–103 °C (2 mmHg) (lit.[31] bp 128–132 °C (5 mmHg)); IR (Nujol) 1720, 1690, 1600, 1580, 1500 cm^{-1}; ^1H NMR (CCl_4) δ 7.8 (m, 2 H), 7.4–7.1 (m, 3 H), 3.0 (t, J = 5 Hz, 2 H), 2.6 (t, J = 5 Hz, 2 H), 2.1 (s, 3 H); MS m/e 176 (M^+), 161, 105, 77, 43.

1-(*p*-Methoxyphenyl)-1,4-pentanedione (2g): mp 54–56 °C (lit.[32] mp 58–59 °C); IR (Nujol) 1720, 1680, 1610, 1580, 1520, 1380 cm^{-1}; ^1H NMR (CCl_4) δ 7.8 (d, J = 8 Hz, 2 H), 6.8 (d, J = 8 Hz, 2 H), 3.7 (s, 3 H), 3.0 (t, J = 6 Hz, 2 H), 2.6 (t, J = 6 Hz, 2 H), 2.1 (s, 3 H); MS m/e 206 (M^+), 135, 92, 77, 43.

1-(*p*-Fluorophenyl)-1,4-pentanedione (2h): ot 120–126 °C (1 mmHg); IR (Nujol) 1980, 1920, 1720, 1680, 1600, 1580, 1500, 840, 820 cm^{-1}; ^1H NMR (CCl_4) δ 7.8 (dd, J = 8, 6 Hz, 2 H), 6.9 (m, 2 H), 3.0 (t, J = 6 Hz, 2 H), 2.6 (t, J = 6 Hz, 2 H), 2.0 (s, 3 H); ^{19}F NMR (60 MHz/CCl_4/CF_3CO_2H) δ 37; MS m/e 194 (M^+), 179, 151, 124, 123, 95, 75, 43. Anal. Calcd for $C_{11}H_{11}FO_2$: C, 68.04; H, 5.67; F, 9.79. Found: C, 67.90; H, 5.50; F, 9.96.

1-(*p*-Fluorophenyl)-4-hydroxy-2-penten-1-one (15h): ot 150–160 °C (1 mmHg); IR (neat) 3400, 3050, 1660, 1630, 1600, 1500, 840 cm^{-1}; ^1H NMR (CD_3COCD_3) δ 7.6 (dd, J = 8, 6 Hz, 2 H), 7.1 (dd, J = 15, 3 Hz, 1 H), 6.8 (m, 2 H), 6.0 (d, J = 15 Hz, 1 H), 4.2 (m, 1 H), 3.0 (s, 1 H), 1.1 (d, J = 5 Hz, 3 H); ^{19}F NMR (60 MHz/CD_3COCD_3/CF_3CO_2H) δ 37; MS m/e 194 (M^+), 176, 164, 151, 123, 95, 75, 43. Anal. Calcd for $C_{11}H_{11}FO_3$: C, 68.04; H, 5.67; F, 9.79. Found: C, 68,30; H, 5.60; F, 9.86.

(2*E*,8*E*)-Deca-2,8-diene-4,7-dione (2i): ot 140–144 °C (1 mmHg); IR (neat) 3030, 1680, 1640, 970 cm^{-1}; ^1H NMR (CCl_4) δ 6.7 (dq, J = 16, 4 Hz, 2 H), 6.0 (d, J = 16 Hz, 2 H), 2.8 (s, 4 H),

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1.7 (d, J = 4 Hz, 6 H); MS m/e 166 (M^+), 97, 82, 69, 43. Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.55; H, 8.54.

(1*E*,7*E*)-1,8-Diphenylocta-1,7-diene-3,6-dione (2j): ot 160–165 °C (1 mmHg); IR (Nujol) 1700, 1670, 1620, 1580, 1500, 970 cm^{-1}; ^1H NMR (CCl_4) δ 7.3 (d, J = 16 Hz, 2 H), 7.0 (m, 10 H), 6.5 (d, J = 16 Hz, 2 H), 2.7 (s, 4 H); MS m/e 290 (M^+), 144, 131, 103, 77, 55. Anal. Calcd for $C_{20}H_{18}O_2$: C, 82.73; H, 6.25. Found: C, 82.88; H, 6.21.

(1*E*)-1-Phenyl-1-heptene-3,6-dione (2k): ot 165–170 °C (0.5 mmHg) (lit.[33] bp 127–128 °C (0.3 mmHg); IR (Nujol) 1720, 1690, 1660, 1610, 1580, 1500, 1000, 760, 700 cm^{-1}; ^1H NMR (200 MHz) δ 7.6 (d, J = 16 Hz, 1 H), 7.4 (m, 5 H), 6.7 (d, J = 16 Hz, 1 H), 3.0–2.7 (m, 4 H), 2.2 (s, 3 H); MS m/e 202 (M^+), 144, 132, 103, 91, 77, 55, 43.

(1*E*,4*E*)-1-Phenyl-6-hydroxy-1,4-heptadien-3-one (15k): ot 150 °C (1.5 mmHg); IR (neat) 3400, 3010, 1660, 1640, 1580, 1500 cm^{-1}; ^1H NMR (CCl_4) δ 7.6 (d, J = 16 Hz, 1 H), 7.4 (m, 5 H), 7.1 (dd, J = 16, 3 Hz, 1 H), 6.9 (d, J = 16 Hz, 1 H), 6.5 (d, J = 16 Hz, 1 H), 4.5 (m, 1 H), 2.1 (s, 1 H), 1.3 (d, J = 5 Hz, 3 H); MS m/e 202 (M^+), 201, 186, 131, 103, 91, 77, 43. Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.93. Found: 77.44; H, 6.63.

(2*E*)-2-Undecene-4,7-dione (21): ot 120–130 °C (1 mmHg); IR (neat) 3050, 1720, 1680, 1640, 970 cm^{-1}; ^1H NMR (CCl_4) δ 6.8 (dq, J = 16, 4 Hz, 1 H), 6.0 (d, J = 16 Hz, 1 H), 2.6–2.2 (m, 6 H), 1.8 (d, J = 4 Hz, 3 H), 1.4–1.1 (m, 4 H), 0.9 (t, J = 7 Hz, 3 H); MS m/e 182 (M^+), 167, 140, 125, 97, 85, 69, 57, 43. Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.97; H, 9.67.

Transformation of 15h into 2h. A mixture of **15h** (50 mg, 0.25 mmol), $Pd_2(dba)_3{\cdot}CHCl_3$ (7 mg, 0.0125 mmol), n-Bu_3P (5 mg, 0.025 mmol), and acetonitrile (2 mL) was refluxed for 16 h. Following a workup similar to that described above, **2h** was isolated, yield: 41 mg (82%). Similarly, **2k** was obtained from **15k** in 75% yield after refluxing for 20 h.

^1H NMR Studies of the Reaction. Under Ar, a mixture of **1a** (11 mg, 0.1 mmol), $Pd_2(dba)_3{\cdot}CHCl_3$ (10 mg, 0.02 mmol), n-Bu_3P (8 mg, 0.04 mmol), and $CDCl_3$ (0.5 mL) was placed into a 5-mm NMR tube; then it was sealed and preserved at rt for 8 h. Three multiplet signals appeared at δ = −12.9, −16.2, and −18.7 when the sample was measured on the Varian XL-200 spectrometer.

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Registry No. **1a**, 3031-66-1; **1b**, 24434-07-9; **1c**, 135468-08-5; **1d**, 105653-97-2; **1e**, 4482-17-1; **1f**, 135468-12-1; **1g**, 135468-06-3; **1h**, 135468-05-2; **1i**, 135468-07-4; **1j**, 135468-10-9; **1k**, 135468-09-6; **1l**, 135468-11-0; **2a**, 110-13-4; **2b**, 2955-65-9; **2c**, 110743-58-3; **2d**, 7018-92-0; **2e**, 495-71-6; **2f**, 583-05-1; **2g**, 2108-54-5; **2h**, 123183-95-9; **2i**, 135468-13-2; **2j**, 135468-14-3; **2k**, 120760-00-1; **2l**, 135468-15-4; $IrH_5(i\text{-}Pr_3P)_2$, 53470-70-5; $Pd_2(dba)_3{\cdot}CHCl_3$, 52522-40-4; Bu_3P, 998-40-3; Ph_3P, 603-35-0; $Pd(OAc)_2$, 3375-31-3.

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Synthesis of α-Methylene β-Lactones, Novel Heterocycles

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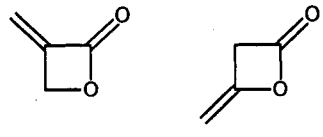
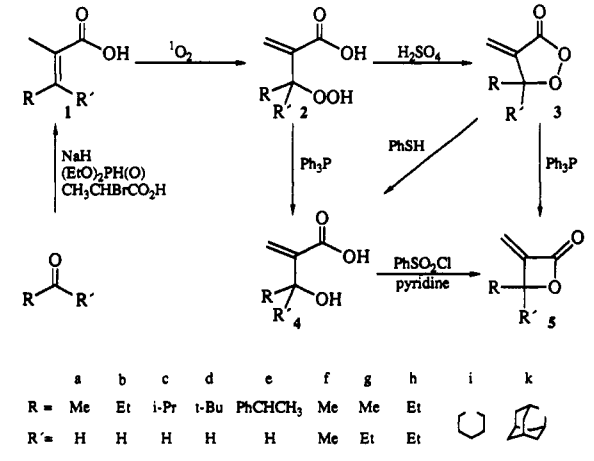
Triphenylphosphine deoxygenation of β-alkyl, β,β-dialkyl-, and β,β-spirocycloalkyl-substituted α-methylene-β-peroxy lactones **3a–k**, which are readily available by photooxygenation of the corresponding α,β-unsaturated carboxylic acids **1**, and cyclization of the resulting α-methylene-β-hydroperoxy acids **2** constitute a convenient method for the preparation of a variety of α-methylene β-lactones **5**. Alternatively, the α-methylene-β-hydroxy carboxylic acids **4** can be directly cyclized by benzenesulfonyl chloride in pyridine into these novel four-membered ring heterocycles **5**.

Ketene dimers (β-methylene β-lactones) have been known for a long time and play a prominent role in organic synthesis.[1] It is surprising that the regioisomeric α-methylene β-lactones are essentially unknown;[2] hitherto no general preparative method existed for this novel heterocycle.



In anticipation that this highly functionalized oxetane ring system could serve as a useful building block, we devised the reaction sequence in Scheme I as a general method of preparation, which makes these labile compounds readily available for the first time. Decisive in this synthetic methodology was convenient access[3] to the α-

Scheme I. Synthetic Pathways to α-Methylene β-Lactones 5



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