3-Aryl-3-butenoic Acids and Their Esters: Practical Synthesis from Diketene by the Palladium-Catalyzed Grignard Coupling Reaction and Application as Monomers for the Radical Copolymerization with Styrene

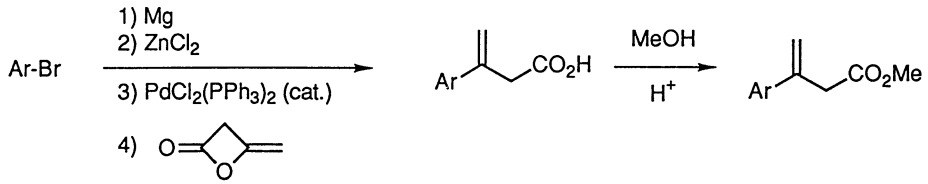
Kenji ITOH,* Tatsumi HARADA, and Hideo NAGASHIMA
Department of Materials Science, Toyohashi University of Technology, Toyohashi, Aichi 441
(Received July 30, 1991)

Synopsis. Treatment of arylmagnesium bromide with an equimolar amount of zinc chloride followed by the reaction with diketene in the presence of a catalytic amount of $PdCl_2(PPh_3)_2$ provided an improved synthetic method for 3-aryl-3-butenoic acids in a large scale. Application as a monomer for the substituted polystyrenes is exemplified by the copolymerization of methyl 3-phenyl-3-butenoate with styrene.

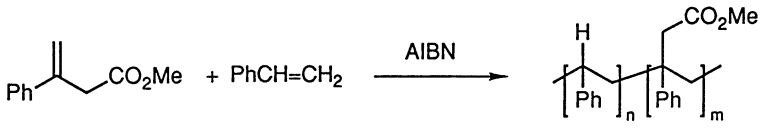
It is well-known that the reactions of diketene with nucleophiles proceed via the cleavage of its carbonyl–oxygen bond, providing general synthetic methods for acetoacetic acid derivatives.[1] Nonetheless, little has been explored on the nucleophilic reactions via the cleavage of its vinyl–oxygen bond. In 1977, we have reported the first nucleophilic substitution of the carboxylate moiety on the vinyl group in diketene by trimethylsilylmethyl moiety of Me_3SiCH_2MgCl with the aid of simple nickel catalysts, which provides a novel synthetic method for 3-(trimethylsilylmethyl)-3-butenoic acid.[2] Although attempted reactions of diketene with other Grignard reagents under similar conditions only resulted in the formation of intractable materials, improved procedures by Fujisawa[3] and Kato[4] provided preparative routes to 3-(alkyl,[3] aryl,[4] benzyl,[4] ethynyl,[4] and vinyl)-3-butenoic acids[4] by judicious choice of either the transition metal catalysts or organometallic nucleophiles.

We are interested in potential utility of 3-aryl-3-butenoic acids and their derivatives as a novel monomer for the polymerization. Since at least several to several ten grams of the monomer are required for the polymerization studies, the preparative process from diketene by Kato,[4] in which diketene is coupled with arylzinc reagents in situ prepared by aryllithium and zinc chloride, is attractive as a potential large scale synthesis for the monomer. However, there are several problems on the manipulation which should be improved in Kato's process; for example, use of rather expensive organolithium reagents and complicated catalyst system consisting of $PdCl_2(PPh_3)_2$ and diisobutylaluminium hydride (DIBAH). In this paper, we describe a modified process for the synthesis of 3-aryl-3-butenoic acids using rather inexpensive and easily available Grignard reagents as the precursor, acid-catalyzed esterification of the resulting 3-aryl-3-butenoic acids, and application of one of the esters to copolymerization with styrene (Scheme 1). After we started this project, Yamamoto and coworkers briefly reported modification of Kato's process to produce 3-phenyl-3-butenoic acid in their studies of asymmetric hydrogenation of 3-aryl-3-butenoic acids.[5] They used rather complicated procedure than the present method, in which the reaction was undertaken in THF with air-sensitive $Pd(PPh_3)_4$ as the catalyst.[5]

Modification of Kato's procedure was made by successive treatment of an ethereal solution of arylmagnesium bromide with $PdCl_2(PPh_3)_2$ (0.5—1 mol%), $ZnCl_2$, and diketene, providing the desired 3-aryl-3-butenoic acids in 50—80% isolated yields. As shown in Table 1, this procedure can be applied to the synthesis of various 3-aryl-3-butenoic acids. Advantages of this improved process are focussed on the use of less expensive Grignard reagents than aryl lithium compounds and of a catalytic amount of $PdCl_2(PPh_3)_2$ without the aluminium co-catalyst. Furthermore, the following two points are useful for the large scale synthesis. First, a sequence of reactions including synthesis of the Grignard reagents from aryl bromides and magnesium,

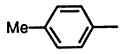
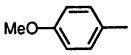


Ar = Phenyl, 1-Naphthyl, o-Tolyl, p-Tolyl, p-Methoxyphenyl, 2-Thienyl



Scheme 1.

Table 1. Palladium-Catalyzed Coupling Reactions of Diketene with Aryl Grignard Reagents

Ar	Cat/%	Time/min	Yield[a]/%
	0.5	30	92 (78)
	1.0	40	94 (79)
	1.0	40	74 (62)
	1.0	40	80 (67)
	1.0	45	63 (42)
	1.0	30	71 (53)

a) Figures in parenthesis are isolated yields after recrystallization.

transmetallation of the resulting Grignard reagents to aryl zinc reagents by the reaction with $ZnCl_2$, and the palladium-catalyzed coupling reactions with diketene can be carried out in one reaction vessel. Second, 3-aryl-3-butenoic acids are generally solids sparingly soluble in hexane, and hence, pure products were obtained only by extraction of the crude acids by hot hexane. In a typical example, 19 g of 3-phenyl-3-butenoic acid was easily obtained from 7.3 g of bromobenzene and 16 ml of diketene.

Addition of Zn(II) salts (one molar equivalent to the Grignard reagents) is crucially important, and an intractable mixtures of the products were formed in their absence. Use of THF instead of ether also caused serious decrease of the yields. Screening of the reaction conditions revealed that other transition metal salts or complexes such as CoI_2, and $NiCl_2(PPh_3)_2$ also gave the acid but in very low yields. Stoichiometric amounts of Ph_2CuLi in ether reacted with diketene to give 3-phenyl-3-butenoic acid in 40—60% isolated yields. However, attempted reactions of PhMgBr in the presence of catalytic amounts of copper salts only resulted in the formation of intractable products.

Esterification of the 3-aryl-3-butenoic acids involves potential formation of 3-aryl-2-butenoates as the by-product because of facile olefin migration. To avoid the olefin isomerization, Yamamoto and coworkers used diazomethane as the reagent for the esterification.[5] However, we found that the acid-catalyzed esterification of 3-phenyl-3-butenoic acid, 3-(*p*-tolyl)-3-butenoic acid, and 3-(1-naphthyl)-3-butenoic acid was made in MeOH in the presence of H_2SO_4 in 60—80% yields. In the case of 3-(*p*-methoxyphenyl)-3-butenoic acid, 3-(2-thienyl)-3-butenoic acid under the same conditions gave a mixture of isomers due to the isomerization of the olefinic bond from the β,γ- to α,β-position.

Radical polymerization studies were made by methyl 3-phenyl-3-butenoate using α,α'-azobis(isobutyronitrile) (AIBN) as the initiator at 60 °C. Since α-substituted styrenes are in general less reactive toward the radical polymerization than styrene, it is reasonable that attempted polymerization of methyl 3-phenyl-3-butenoate itself was in failure. However, copolymerization with styrene successfully produced new polystyrenes including methoxycarbonylmethyl group as the side chain. As shown in Table 2, average molecular weights of the formed polymers were from 13000 to 75000. With higher molar ratios of styrene monomer to methyl 3-phenyl-3-butenoate, copolymers including lower ratios of the ester component with relatively higher molecular weights were formed in high yields. In contrast, with lower molar ratios of styrene monomer to methyl 3-phenyl-3-butenoate were formed copolymers including relatively higher ratios of the ester component but in low yields. Reactivity of styrene (M_1) to methyl 3-phenyl-3-butenoate (M_2) at 60 °C in the copolymerization was estimated by the curve-fitting method as r_1=6.3 and r_2=0.02.

Table 2. Radical Copolymerization of Methyl 3-Phenyl-3-Butenoate with Styrene at 60 °C

Monomer ratio[a]	Copolymer composition	Time	Conversion	M_n[b]	M_w/M_n[b]
		h	%	$\times10^{-4}$	
1:1	1:5	12	2.5	1.4	1.5
		48	9.5	1.3	1.5
1:5	1:12	12	9.6	2.0	1.5
		48	37.2	2.5	1.7
		96	52.9	2.9	2.0
1:10	1:24	12	18.0	2.9	1.6
		48	50.0	3.5	1.8
1:20	1:35	12	25.9	3.6	1.7
		48	79.1	6.1	1.8
1:40	1:73	12	33.8	4.6	1.7
		48	91.5	7.5	2.2

a) Molar ratios of methyl 3-phenyl-3-butenoate to styrene. b) Determined by GPC based on polystyrene.

In conclusion, a simple and versatile synthetic preparative procedure for 3-aryl-3-butenoic acids and their esters suitable to large scale synthesis was established. Furthermore, utility of these compounds as monomer was exemplified by copolymerization of styrene with methyl 3-phenyl-3-butenoate to produce new polystyrenes including polar methoxycarbonylmethyl appendages in their side chain.

Experimental

All manipulations were carried out under nitrogen atmosphere with dry solvents. Reagents were distilled before use. NMR spectra were measured in $CDCl_3$ by a JEOL GX-270 spectrometer (^1H; 270 MHz, ^{13}C; 67.8 MHz) and their δ-values (ppm from TMS) are listed below. IR spectra were measured by a Jasco IR A-3 spectrometer and recorded with the wavenumber. Elemental analysis was made by a Yanaco CHN meter. Mass spectra were measured by a Hitachi M-80B spectrometer. The Grignard reagents described below were prepared from the corresponding aryl bromide and magnesium, which can be stored in a refrigerator as a stock solution. Use of either the freshly prepared Grignard reagents or the stock solution provided similar yields of the desired acids.

General Procedure for the Preparation of 3-Aryl-3-butenoic Acid from Diketene and Arylmagnesium Bromide: The Grignard reagent prepared from Mg turnings (7.3 g, 0.3 mol),

aryl bromide (0.285 mol), and ether (200 ml) was diluted with additional ether (100 ml). Anhydrous $ZnCl_2$ (35 g, 0.257 mmol) was gradually added to the solution and stirred for 45 min to give suspension of white solids in brown solution. Then, $PdCl_2(PPh_3)_2$ (0.726 g, 0.001 mol, 0.5 mol%) and a solution of diketene (16 ml, 0.207 mol) in ether (400 ml) were added dropwise and the mixture was stirred for 30 min. The reaction mixture was poured into a cold 2 equiv HCl aq, and the mixture was extracted with ether. The acid was extracted from the organic layer by 3 equiv NaOH aq. The aqueous layer was acidified by 6 equiv HCl and extracted with ether. The extracts were combined and dried over $MgSO_4$. Removal of the solvents afforded crude 3-aryl-3-butenoic acid (60—80%). This crude acid contained no organic impurities detectable by ^1H NMR spectrum, and can be used for the esterification without further purification. Most of the acids can be purified by recrystalization from hot hexane.

3-Phenyl-3-butenoic Acid: White crystals. Mp 46—47 °C [lit, 46—47 °C].[4,5] ^1H NMR δ=3.54 (2H, s, CH_2CO), 5.26, 5.58 (s, 1H, each, olefin), 7.28—7.45 (m, 5H, Ph). ^{13}C NMR δ=40.8, 116.8, 125.8, 128.0, 128.5, 139.4, 140.2, 177.2. IR (KBr) 1700. Found: C, 74.06; H, 6.21%. Calcd for $C_{10}H_{10}O_2$: C, 74.01; H, 6.25%.

3-(1-Naphthyl)-3-butenoic Acid: White solids. Mp 74.5 °C. ^1H NMR δ=3.56 (s, 2H, CH_2CO), 5.35, 5.62 (s, 1H each, olefin), 7.34—8.03 (m, 7H, aromatic). ^{13}C NMR δ=43.3, 120.3, 125.2, 125.3, 125.4, 125.8, 126.1, 127.8, 128.4, 130.9, 133.7, 139.5, 140.3, 177.1. IR (KBr) 1710. Found: C,79.30; H, 5.76%. Calcd for $C_{14}H_{12}O_2$: C, 79.23; H, 5.70%.

3-(*o*-Tolyl)-3-butenoic Acid: Extraction of the crude acid by hot hexane (100 ml×3) followed by the concentration of the combined extracts gave the pure acid as a yellow oil; ^1H NMR δ=2.32 (s, 3H, Me), 3.39 (s, 2H, CH_2CO), 5.13, 5.41 (s, 1H each, olefin), 7.14—7.18 (m, 4H, aromatic). ^{13}C NMR δ=19.4, 42.5, 118.7, 125.2, 127.0, 128.0, 129.9, 134.5, 140.8, 141.0, 176.6. IR (neat) 1715. Found: C, 74.86; H, 6.95%. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86%.

3-(*p*-Tolyl)-3-butenoic Acid: White solids. Mp 106—107 °C [lit, 113—114 °C].[4] ^1H NMR δ=2.34 (s, 3H, Me), 3.52 (s, 2H, CH_2CO), 5.20, 5.54 (s, 1H each, olefin), 7.13, 7.32 (d, J=8.3 Hz, 2H each, aromatic). ^{13}C NMR δ=20.6, 40.5, 115.4, 125.1, 128.6, 136.0, 137.2, 139.4, 176.8. IR (KBr) 1700. Found: C, 74.93; H, 6.84%. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86%.

3-(*p*-Methoxyphenyl)-3-butenoic Acid: Yellow solids. ^1H NMR δ=3.52 (s, 2H, CH_2CO), 3.81 (s, 3H, OMe), 5.16, 5.50 (s, 1H each, olefin), 6.86, 7.38 (d, J=8.8 Hz, 2H each, aromatic). ^{13}C NMR δ=40.6, 54.9, 113.3, 114.6, 126.4, 131.4, 139.0, 158.9, 176.0. IR (KBr) 1700. Found: C, 68.76; H, 6.28%. Calcd for $C_{11}H_{12}O_3$: C, 68.74; H, 6.29%.

3-(2-Thienyl)-3-butenoic Acid: Pale yellow solids; yield: 2.52 g (53%); mp 65—66 °C. ^1H NMR δ=3.51 (s, 2H, CH_2CO), 5.14 and 5.61 (s, 1H each, olefin), 6.96 (dd, J=3.4, 5.4 Hz, 1H, 4-H on the thiophene ring), 7.04 (d, J=3.4 Hz, 1H, 5-H on the thiophene ring), 7.18 (d, J=5.4 Hz, 3-H on the thiophene ring). ^{13}C NMR δ=40.8, 114.9, 123.9, 124.6, 127.1, 133.5, 143.2, 176.0. IR (KBr) 1680. Found: C, 57.13; H, 4.86. Calcd for $C_8H_8O_2S$: C, 57.12; H, 4.79%.

Preparation of Methyl Esters: General Procedure: A mixture of the acid (0.13 mol), H_2SO_4 (3 ml, 56 mmol), and methanol (100 ml) was heated under reflux for 30 min. After cooling, H_2SO_4 was neutralized with aqueous $NaHCO_3$ (9.5 g in 100 ml water). Methanol was removed under a reduced pressure and the residue was extracted with CH_2Cl_2. The combined extracts were dried over $MgSO_4$, concentrated, and purified by distillation.

Methyl 3-Phenyl-3-butenoate: Colorless oil; yield 76%; bp 98—106 °C/4 mmHg. ^1H NMR δ=3.51 (s, 2H, CH_2CO), 3.62 (s, 3H, OMe), 5.22, 5.54 (s, 1H each, olefin), 7.25—7.44 (m, 5H, aromatic). ^{13}C NMR δ=40.5, 51.4, 115.7, 125.2, 127.3, 127.9, 139.1, 140.2, 171.1. IR (neat) 1740. HAMS; Found: m/z 176.0836. Calcd for $C_{11}H_{12}O_2$: M, 176.0837.

Methyl 3-(*p*-Tolyl)-3-butenoate: Colorless oil; yield 77%; bp 110—120 °C/4 mmHg. ^1H NMR δ=2.33 (s, 3H, Me), 3.50 (s, 2H, CH_2CO), 3.65 (s, 3H, OMe), 5.18, 5.51 (s, 1H each, olefin), 7.13, 1.32 (d, J=8.3 Hz, 2H each, aromatic). ^{13}C NMR δ=20.7, 40.7, 51.6, 115.0., 125.3, 128.7, 136.4, 137.2, 140.2, 171.4. IR (neat) 1740. HAMS; Found: m/z 190.0994. Calcd for $C_{12}H_{14}O_2$: M, 190.0992.

Methyl 3-(1-Naphthyl)-3-butenoate: Pale yellow oil; yield: 65%; bp 153—156 °C/5 mmHg. ^1H NMR δ=3.54 (s, 2H, CH_2CO), 3.59 (s, 3H, OMe), 5.31, 5.59 (s, 1H each, olefin), 7.33—8.06 (m, 7H, aromatic). ^{13}C NMR δ=43.6, 51.7, 119.7, 125.2, 125.3, 125.4, 125.7, 126.0, 127.7, 128.3, 131.0, 133.7, 139.7, 140.9, 171.3. IR (neat) 1740. Found: C, 79.62; H, 6.28%. Calcd for $C_{15}H_{14}O_2$: C, 79.62; H, 6.24%.

General Procedure of Copolymerization of Methyl 3-Phenyl-3-butenoate with Styrene: A representative experiment was given below. A mixture of methyl 3-phenyl-3-butenoate (2.3 g, 13 mmol), styrene (1.5 ml, 13 mmol), and AIBN (17 mg, 0.1 mmol) was freezed and degassed in a pyrex tube. The tube was sealed under vacuum, and then the mixture was heated at 60 °C for 12 h. The resulting solution was poured into methanol. The formed precipitates were separated by filtration, washed with methanol, and dried under vacuum. The crude polymer was dissolved in benzene and poured into methanol. The precipitates were filtered, washed with methanol, and dried under vacuum to give the copolymer as white solids (92 mg). ^1H NMR δ=0.9—2.7 (br, methylene, methine), 2.8—3.05 (br, CH_2CO), 3.1—3.4 (br, CH_2CO), 6.0—7.3 (br, aromatic ring).

The authors are grateful to Dr. Tsutomu Takeichi and Mr. Seigou Kawaguchi of Toyohashi University of Technology for their helpful discussion on the copolymerization of methyl 3-phenyl-3-butenoate with styrene. One of the authors (K. I.) is grateful to the Ministry of Education, Science and Culture for Grant-in-Aid for The Scientific Research No. 63470073.

References

1) For reviews; T Kato, *Acc. Chem. Res.*, **7**, 265 (1974). R. J. Clemens, *Chem. Rev.*, **86**, 241 (1986).

2) K. Itoh, M. Fukui, and Y. Kurachi, *J. Chem. Soc., Chem. Commun.*, **1977**, 500. K. Itoh, T. Yogo, and Y. Ishii, *Chem. Lett.*, **1977**, 103.

3) T. Fujisawa, T. Sato, Y. Gotoh, M. Kawashima, and T. Kawara, *Bull. Chem. Soc. Jpn.*, **55**, 3555 (1982).

4) Y. Abe, M. Sato, M., H. Goto, R. Sugawara, E. Takahashi, and T. Kato, *Chem. Pharm. Bull.*, **31**, 4346 (1983).

5) K. Yamamoto, K. Ikeda, and L. K. Yin, *J. Organomet. Chem.*, **370**, 319 (1989).