Journal of Organometallic Chemistry 694 (2009) 3626–3632

Contents lists available at ScienceDirect

Journal of Organometallic Chemistry

journal homepage: www.elsevier.com/locate/jorganchem

A high hydroarylation activity of K_2PtCl_4/AgOTf catalyst in the reaction of propiolic acid with unactivated and activated arenes

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ARTICLE INFO

Article history:
Received 19 May 2009
Received in revised form 4 July 2009
Accepted 7 July 2009
Available online 9 July 2009

Keywords:
Platinum catalyst
Hydroarylation
Alkyne
cis-Cinnamic acid
Propiolic acid

ABSTRACT

A mixed catalyst K_2PtCl_4/AgOTf showed the highest activity for hydroarylation of propiolic acid, among palladium and platinum catalysts. This catalyst was effective for hydroarylation with less reactive benzene to give *cis*-cinnamic acid in good yield. The hydroarylation with toluene gave a higher yield of hydroarylation products than that with benzene and resulted in *ortho*/*para* orientation with an almost statistical ratio, suggesting that the result is very close to that of the Friedel-Crafts alkylation with methyl bromide or *p*-nitrobenzyl chloride. Hydroarylation of propiolic acid with other electron-rich arenes proceeded efficiently in the presence of the K_2PtCl_4/AgOTf catalyst in trifluoroacetic acid forming *cis*-cinnamic acids in good to high yields. This method was also applied to hydroarylation of ethyl propiolate.

1. Introduction

Direct C–H bond functionalization has recently gained increasing interest in organic chemistry [1]. This method has several advantages compared with conventional synthetic methods and does not require prefunctionalization because it uses only C–H bonds instead of reactive groups as reaction site for functionalization. It not only reduces reaction steps but also avoids use of toxic halogenated compounds, thus simple and cheap hydrocarbons can be used as starting materials. Furthermore, this method is also favorable from the viewpoint of atom economy because some functional groups are used as leaving groups, which are not incorporated into the products. Therefore, this method provides ideal transformation that is clean, simple and cheap.

Recently, many synthetic methods for hydroarylation of alkynes using transition metal catalysts have been reported [2]. Several transition metal compounds catalyze hydroarylation of alkynes in a manner of C–H bond activation or electrophilic substitution [3–13]. Transition metal catalyzed-addition reactions of arenes having directing groups such as carbonyl, imino and nitrile groups via chelation-assisted C–H bond functionalization have been extensively studied [1h,i]. A chelation-assisted reaction of arenes to alkynes is catalyzed by several transition metal compounds to afford *ortho*-alkenylation products [14–18]. Similarly, intramolecular reaction of arylated alkynes catalyzed by transition metal compounds produces cyclic aromatics and heterocycles [19–24].

Alternatively, $Pd(OAc)_2$-catalyzed hydroarylation of alkynes proceeds via electrophilic aromatic substitution under very mild conditions to afford *cis*-aryl substituted alkenes [5a,b,d]. However, hydroarylation of ethyl propiolate forms diethyl (1*E*,3*Z*)-4-arylbuta-1,3-diene-1,3-dicarboxylates as a by-product and results in low selectivity and yield of the desired product. On the other hand, we initially found that hydroarylation of ethyl propiolate proceeded selectively producing cinnamates without forming buta-1,3-diene-1,3-dicarboxylates when the Pt(II) catalyst $PtCl_2$/AgOAc was used instead of $Pd(OAc)_2$ [5b]. However, the activity of the $PtCl_2$/AgOAc catalyst was still low and required improvement. Hence, we examined the silver additive and found that the $PtCl_2$/AgOTf catalytic system improved the reactivity and selectivity for hydroarylation of propiolic acid derivatives [25]. However, the $PtCl_2$/AgOTf catalyst showed a low activity toward less reactive aromatics and could not be applied to the hydroarylation with a representative aromatic compound such as benzene. To increase the activity to benzene, we studied a more reactive Pt catalyst for hydroarylation of propiolic acids and found preliminary that K_2PtCl_4/AgOTf catalyst improved reactivity and afforded a hydroarylation product in good yield even for the less reactive benzene [26]. Thus, to verify the utility of the K_2PtCl_4/AgOTf catalyst and the scope of this hydroarylation reaction, we further studied the reaction with toluene and other aromatics and the hydroarylation of propiolic esters. Here, we report the details of K_2PtCl_4/AgOTf-catalyzed hydroarylation of propiolic acids.

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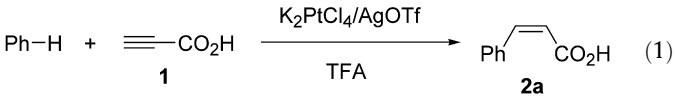
doi:10.1016/j.jorganchem.2009.07.008

2. Results and discussion

2.1. Hydroarylation of propiolic acid with benzene

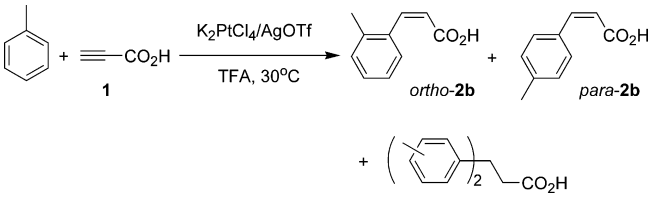
K_2PtCl_4, which is one of the most readily available and cheapest platinum salts, is stable, non-hygroscopic, and easy to handle without any precaution such as inert atmosphere. Therefore, K_2PtCl_4 was chosen and used as a pre-catalyst for hydroarylation of propiolic acid **1** with benzene. The reaction of a parent arene, benzene, with **1** was examined using the K_2PtCl_4/AgOTf catalyst (Eq. (1), Table 1). The hydroarylation is not been applicable to benzene because of its low reactivity in the case of palladium or platinum catalysts. The reaction with 3 equiv. of benzene afforded (*Z*)-cinnamic acid **2a** in 50% yield (entry 1). The reaction in the absence of AgOTf reduced the yield of **2a** (entry 2). Using 6 equiv. of benzene and elevation of temperature also improved the yield (entries 3 and 4). Further increasing the amount of benzene did not improve the yield (entry 5). Similar yields were obtained even when 1% K_2PtCl_4 and 4% AgOTf were used (entries 6 and 7). Increasing catalyst loading with the same catalyst ratio (2.5% K_2PtCl_4/10% AgOTf) slightly improved the yield to 66% (entry 8). A significant difference between catalysts (K_2PtCl_4/AgOTf, $PtCl_4$/AgOTf, $PtCl_2$/AgOTf, and $Pd(OAc)_2$) was observed. Although the reaction in the presence of $PtCl_4$/AgOTf catalyst gave a good yield of **2a**, it resulted in a low *Z*/*E* ratio (entry 9). In the reactions using $PtCl_2$/AgOTf and $Pd(OAc)_2$, the yields of **2a** were only 35% and 10%, respectively (entries 10 and 11), and much lower than that in the case of K_2PtCl_4/AgOTf.



(1)

2.2. Hydroarylation of propiolic acid with toluene

Methyl group is activating and *ortho*/*para* directing for electrophilic aromatic substitution. Hydroarylation of alkynes with toluene was expected to indicate similar phenomena to the Friedel-Crafts alkylation and related reactions. Then, we examined the reaction of propiolic acid **1** with toluene in the presence of K_2PtCl_4/AgOTf catalyst. In the case of toluene, *ortho*- and *para*-isomers of the hydroarylation product **2b** were obtained together with 3,3-ditolylpropionic acid (Eq. (2), Table 2). When 2.5% K_2PtCl_4 and 5% AgOTf were used, a mixture of the *ortho*- and *para*-isomers of **2b** was obtained in 72% yield with a statistical ratio (*ortho*/*para* = 2.0/1) (entry 1). After complete consumption of **1**, the yield of **2b** was improved to 79% (entry 2). At the same time, the ratio of *ortho*- and *para*-isomers was also increased to 2.8/1. When 1% K_2PtCl_4 and 4% AgOTf were used, a similar result was obtained after the consumption of **1** (entry 3). Extension of the reaction time resulted in a larger amount of 3,3-ditolylpropionic acid along with an increased ratio of *ortho*/*para* (3.9/1) (entry 4). Such a tendency was clearly observed over the time course of the reaction (Fig. 1). At first, the reaction gave *ortho*- and *para*-**2b** in an almost statistical ratio (1.8–2.0/1). After that, only the amount of *para*-**2b** decreased along with an increased amount of 3,3-ditolylpropionic acid. As the amount of *para*-**2b** decreased, that of *ortho*-**2b** remained unchanged. This suggests that only *para*-**2b** participates in the further reaction leading 3,3-ditolylpropionic acid. It is considered that the *ortho*-methyl group in *ortho*-**2b** prevents the further reaction probably due to steric hindrance.



(2)

The hydroarylation of propiolic acid with toluene showed *ortho*/*para* orientation, being consistent with the result of usual Friedel-Crafts reactions. The *ortho*/*para* ratio observed in this hydroarylation was 2:1 (the statistically expected ratio). This result is very close to that of the Friedel-Crafts alkylation reactions [27]. Judging from the results of the Friedel-Crafts alkylation by methyl bromide (*ortho*/*para* = 1.9/1) and *p*-nitrobenzyl bromide (*ortho*/*para* = 1.7/1), this hydroarylation reaction is presumed to involve a highly reactive species which does not affect *ortho* substitution of toluene because of a less hindered terminal alkyne. Accordingly, the hydroarylation of propiolic acid leads to the lack of positional selectivity.

2.3. Hydroarylation of propiolic acid with other electron-rich arenes

Hydroarylation of **1** with various electron-rich arenes gave corresponding cinnamic acids **2** in high yields (Eq. (3), Table 3). Similar results were also obtained when 1% K_2PtCl_4 and 4% AgOTf were used. Reactions of **1** with xylene gave **2c** in 93% and 96% yields (entries 1 and 2). It is noteworthy that the reaction with xylene afforded the hydroarylation product in an almost quantitative yield. Reactions of mesitylene and pentamethylbenzene gave cinnamic acids **2d** and **2e** in high yields, respectively (entries 3–5). Less reactive bromomesitylene having an electron-withdrawing bromine atom gave **2f** in sufficient yield although the reaction was carried

Table 1
K_2PtCl_4/AgOTf-catalyzed hydroarylation of **1** with benzene affording cinnamic acid.[a]

Entry	Catalyst (mmol)		Benzene (mmol)	Temperature (°C)	Time (h)	Yield (%)	*Z*/*E*[b]
1	K_2PtCl_4/AgOTf	0.05/0.1	6	r.t.	72	50	95/5
2	K_2PtCl_4	0.05	6	r.t.	70	31	85/15
3	K_2PtCl_4/AgOTf	0.05/0.1	12	r.t.	70	54	99/1
3	K_2PtCl_4/AgOTf	0.05/0.1	12	40	40	61	93/7
5	K_2PtCl_4/AgOTf	0.05/0.1	24	40	45	55	98/2
6	K_2PtCl_4/AgOTf	0.02/0.08	12	40	40	53	98/2
7	K_2PtCl_4/AgOTf	0.02/0.08	12	r.t.	75	58	98/2
8[c]	K_2PtCl_4/AgOTf	0.05/0.2	12	40	25	66	93/7
9[d]	$PtCl_4$/AgOTf	0.05/0.2	12	40	25	56	64/36
10	$PtCl_2$/AgOTf	0.05/0.1	12	r.t.	70	35	99/1
11	$Pd(OAc)_2$	0.05	12	r.t.	24	11	99/1

[a] Reaction conditions: K_2PtCl_4, AgOTf, benzene, **1** (2 mmol) and TFA (1 mL).
[b] Isolated yield based on **1**. *Z*/*E* ratio was determined by ^1H NMR.
[c] 3,3-Diphenylpropionic acid was formed in 2% yield.
[d] 3,3-Diphenylpropionic acid was formed in 7% yield.

Table 2
K_2PtCl_4/AgOTf-catalyzed hydroarylation of **1** with toluene.[a]

Entry	Catalyst[b]	Time (h)	Yield (%)[c]			Ratio
			o-**2b** (*Z*/*E*)	*p*-**2b** (*Z*/*E*)	$Tol_2CHCH_2CO_2H$	(*o*-**2b**/*p*-**2b**)
1	I	25	48 (>99/1)	24 (96/4)	6	2.0/1
2	I	42	58 (99/1)	21 (84/16)	16	2.8/1
3	II	40	49 (99/1)	19 (83/17)	18	2.6/1
4	II	60	53 (99/1)	14 (65/35)	23	3.9/1

[a] Reaction conditions: K_2PtCl_4, AgOTf, toluene (6 mmol), **2b** (2 mmol), TFA (1 mL) at 30 °C.
[b] Catalyst I: K_2PtCl_4 (0.05 mmol) and AgOTf (0.1 mmol). Catalyst II: K_2PtCl_4 (0.02 mmol) and AgOTf (0.08 mmol).
[c] The yields are based on **2b** and determined by ^1H NMR.

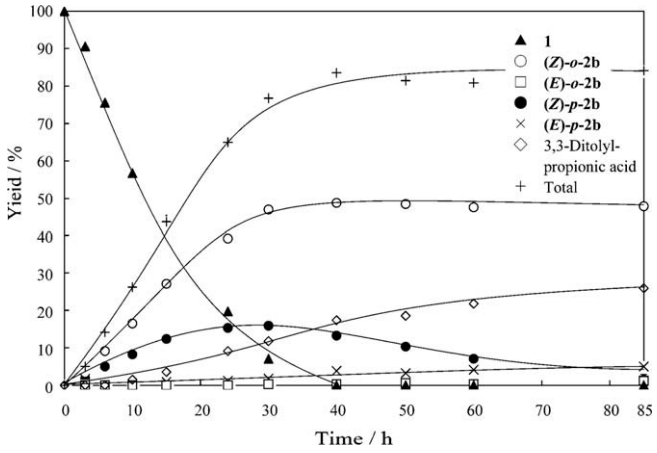
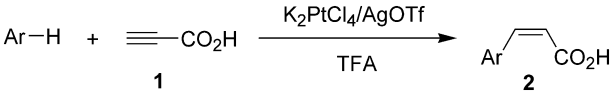


Fig. 1. Time course of the hydroarylation of **1** with toluene. Reaction conditions: K_2PtCl_4 (0.02 mmol), AgOTf (0.08 mmol), toluene (6 mmol), **1** (2 mmol), pentadecane (20 mg, as an internal standard) and TFA (1 mL) at 30 °C. The yields were based on **1** and determined by ^1H NMR.

out at 40 °C (entry 6). Reaction of naphthalene also gave **2g** in 83% yield (entry 7). Next, the reaction of more sterically hindered arene, 1,4-di-*tert*-butylbnezene was examined because the reaction of **1** was applicable to sterically crowded arenes such as mesitylene, pentamethylbenzene and bromomesitylene. The reaction of 1,4-di-*tert*-butylbnezene proceeded to afford **2h** in 75% yield although such yield was lower than that of xylene (entry 8).



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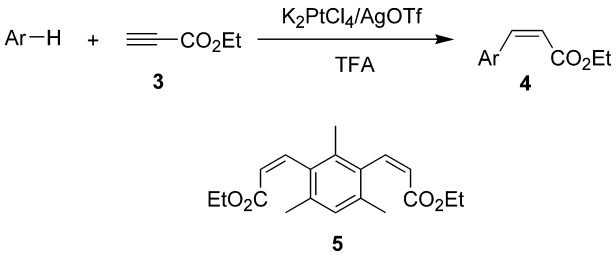
2.4. Hydroarylation of ethyl propiolate with electron-rich arenes

To verify the scope of this hydroarylation catalyzed by K_2PtCl_4/AgOTf, we examined the reaction of ethyl propiolate **3** (Eq. (4)). Results are shown in Table 4. The reaction of **3** with xylene at room temperature gave **4a** and **2c** in 69% and 14% yields, respectively (entry 1). The formation of **2c** is derived from the hydrolysis of **4a**, resulting in the low selectivity of **4a**. However, the total yield of hydroarylation products **4a** and **2c** was good (83%). Because complete conversion of **3** was observed from GC analysis of the reaction mixture, it was considered that the hydroarylation with less reactive arenes competed with hydrolysis of products. In the hydroarylation of ethyl propiolate **3**, therefore, reactive electron-rich arenes are the best substrate for hydroarylation. The reaction of mesitylene gave **4b** and **5a** in 85% and 10% yields, respectively (entry 2). The reaction of more electron-rich pentamethylbenzene gave cinnamate **4c** in 94% yield (entry 3). In the case of 2,4,6-trimethylphenol, the reaction gave the mono-alkenylated product **4d** and the di-alkenylated product **5b** similarly to the reaction of mesitylene. In this case, the use of 3 equiv. of 2,4,6-trimethylphenol afforded **4d** selectivity (entry 4). Conversely, an excess amount of **3** afforded **5b** in good yield as the main product (entry 5).



(4)

Table 3
K_2PtCl_4/AgOTf-catalyzed hydroarylation of **1** with various arenes.[a]

Entry	Arene	Catalyst[b] (°C)	Temperature (h)	Time[c] (%)	Product	Yield
1	*p*-Xylene	I	r.t.	25	**2c**	93
2	*p*-Xylene	II	r.t.	40	**2c**	96
3	Mesitylene	I	r.t.	15	**2d**	96
4	Mesitylene	II	r.t.	12	**2d**	95
5[d]	Pentamethylbenzene	I	r.t.	15	**2e**	96
6[e]	Bromomesitylene	I	40	40	**2f**	88
7[f]	Naphthalene	I	40	40	**2g**	83 (*Z*/*E* = 93/7)
8[g]	*p*-Di-*tert*-butylbenzene	II	r.t.	45	**2h**	75

[a] Reaction conditions: catalyst, arene (6 mmol), **1** (2 mmol) and TFA (1 mL).
[b] Catalyst I: K_2PtCl_4 (0.05 mmol) and AgOTf (0.1 mmol). Catalyst II: K_2PtCl_4 (0.02 mmol) and AgOTf (0.08 mmol).
[c] Isolated yields based on **1**. *Z*-Isomers were obtained exclusively (*Z*/*E* > 95/5).
[d] Pentamethylbenzene (3 mmol) was used. CH_2Cl_2 (0.25 mL) was added.
[e] CH_2Cl_2 (0.5 mL) was added.
[f] Naphthalene (4 mmol) was used. $Cl(CH_2)_2Cl$ (0.75 mL) was added. Naphthalene reacted only at the 1 position to give product **2g**.
[g] CH_2Cl_2 (1 mL) was added.

Table 4
K_2PtCl_4/AgOTf-catalyzed hydroarylation of **3** with electron-rich arenes.[a]

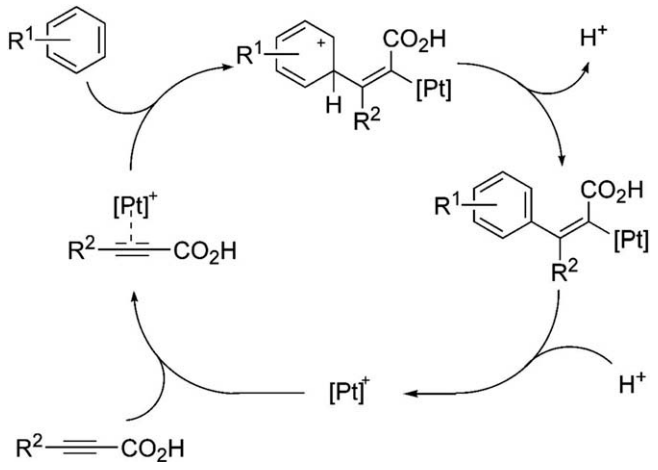
Entry	Arene	Time (h)	Product and yield (%)[b]			
1	*p*-Xylene	25	**4a** (*Z*/*E* = 98/2)	69	**2c** (*Z*/*E* = 97/3)	14
2	Mesitylene	15	**4b**	(85)	**5a**	10
3[c]	Pentamethylbenzene	10	**4c**	(94)		
4[d]	2,4,6-Trimethylphenol	25	**4d**	82	**5b**	<10
5[e]	2,4,6-Trimethylphenol	45	**4d**	18	**5b**	64

[a] Reaction conditions: K_2PtCl_4 (0.05 mmol), AgOTf (0.1 mmol), arene (4 mmol), **3** (2 mmol), TFA (1 mL) at room temperature.
[b] Isolated yields based on **3**. The yields in parentheses are determined by GC.
[c] CH_2Cl_2 (0.25 mL) was added.
[d] 2,4,6-Trimethylphenol (6 mmol) was used.
[e] 2,4,6-Trimethylphenol (2 mmol) and **3** (4.8 mmol) were used. The yields were based on 2,4,6-trimethylphenol.

2.5. Mechanistic consideration

Palladium acetate-catalyzed hydroarylation of alkynes with arenes was initially thought to proceed via C–H activation of the arene followed by addition of a palladium–arene bond across the alkyne [5], but mechanistic studies based on kinetic isotope effects have suggested that the reaction proceeds by electrophilic aromatic substitution with a metal-activated alkyne [6]. Since both Pd- and Pt-catalyzed hydroarylation reactions take place under mild reaction conditions, this Pt-catalyzed hydroarylation is also considered to proceed via an electrophilic aromatic substitution mechanism. The preferential hydroarylation in the cases of electron-rich arenes and *ortho*/*para* orientation in the reaction with toluene are in accord with the electrophilic aromatic substitution. This consideration is further supported by the result of the hydroarylation of cyclohexene with toluene reported by Karshtedt et al. [28], which shows *ortho*/*para* orientation (*orhto*:*meta*:*para* = 31:6:63) and the enhanced yields of hydroarylation products compared with the reaction with benzene. The electrophilic aromatic substitution mechanism is shown in Scheme 1. The highly reactive, cationic Pt species generated from K_2PtCl_4 and AgOTf compound initiates the reaction by forming a complex with a propiolic acid. The resulting activated propiolic acid complex attacks an arene electrophilically forming a Wheland intermediate. Proton release followed by protonolysis of a platinum-vinyl species results in the formation of a cinnamic acid with concomitant regeneration of an active Pt species, which completes the catalytic cycle.

In the formation of a diarylpropionic acid, the resulting cinnamic acid undergoes a second hydroarylation induced by the Pt catalyst in a similar manner as that described above. In addition to Pt-catalysis, acid-catalyzed hydroarylation is also possible for the second hydroarylation because it was reported that the hydroarylation of ethyl *p*-methylcinnamate with 2-naphthol was catalyzed by TFA to give dihydrocoumarin [29].



Scheme 1.

3. Conclusion

We have demonstrated that K_2PtCl_4/AgOTf catalyst has the highest hydroarylation activity among platinum and palladium catalysts examined so far [5,25]. In addition, among the Pt catalyst precursors, K_2PtCl_4 is readily available, stable and easy to handle. The K_2PtCl_4/AgOTf catalyst worked efficiently in the hydroarylation of propiolic acids and the esters to afford *cis*-cinnamic acids and esters in high yields in most cases. Noteworthy is the high hydroarylation activity of the K_2PtCl_4/AgOTf catalyst toward less reactive benzene and toluene. Therefore, the hydroarylation catalyzed by this catalyst may bring about practical applications for synthesis of functionalized cinnamic acids and the derivatives.

4. Experimental

All solvents and reagents were commercially available and used as received without further purification. All reactions were conducted in a dry Pyrex tube with a rubber septum. ^1H and ^{13}C NMR spectra were recorded on a JEOL JNM-AL 300 FT-NMR (300 MHz) system using TMS as internal standard. Melting points were measured with a YANACO micro melting apparatus and were uncorrected. GC analysis was performed on Shimadzu GC-14B using the capillary column DB-1 (15 m × 0.53 mm internal diameter × 1.5 μm film thickness) equipped with a flame ionization detector. GC yield was determined by the internal standard method using *n*-pentadecane or *n*-heptadecane as internal standard. Mass spectra were measured on Shimadzu GC–MS 5020A. Elemental analysis was performed by the Service Center of the Elementary Analysis of Organic Compounds, Faculty of Science, Kyushu University.

4.1. General procedure for K_2PtCl_4/AgOTf-catalyzed hydroarylation of *1*

After a mixture of K_2PtCl_4 (0.05 mmol) and AgOTf (0.10 mmol) in TFA (1 mL) was stirred at room temperature for 10 min, an arene and **1** were added and the mixture was stirred at the desired temperature. After a certain period, the reaction mixture was poured into water (20 mL), neutralized with $NaHCO_3$, and washed with Et_2O (20 mL). The ethereal layer was then extracted with aqueous 2 M NaOH (10 mL × 3). The combined aqueous layer was washed with Et_2O (20 mL), acidified with aq. HCl (ca. 36%) and extracted with CH_2Cl_2 (20 mL × 3). The organic layer was dried over

anhydrous Na_2SO_4 and concentrated under reduced pressure, affording cinnamic acids.

4.2. General procedure for K_2PtCl_4/AgOTf-catalyzed hydroarylation of **3**

After a mixture of K_2PtCl_4 (0.05 mmol) and AgOTf (0.1 mmol) in TFA (1 mL) was stirred at room temperature for 10 min, an arene and **3** were added and the mixture was stirred at the desired temperature. After the reaction, the mixture was poured into water (20 mL), neutralized with $NaHCO_3$, and extracted with diethyl ether (20 mL × 3). The ethereal layer was dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel using a mixture of ethyl acetate and hexane as eluents.

4.3. Procedure for investigating the time course of hydroarylation of **1** with toluene

After a mixture of K_2PtCl_4 (0.02 mmol) and AgOTf (0.08 mmol) in TFA (1 mL) was stirred at room temperature for 1 h, toluene (6 mmol), *n*-pentadecane (ca. 18 mg, as internal standard) and **1** (2 mmol) were added, and the reaction mixture was stirred at room temperature (30 °C). After a certain period, a portion of the reaction mixture was analyzed by ^{1}H NMR. The yields of the products and the conversion of **1** were determined using the internal standard method. Results are given in Fig. 1.

4.4. (2Z)-Cinnamic acid (**2a**) [30]

Colorless crystals; m.p. 65–66.5 °C (hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.95 (d, J = 12.6 Hz, 1H, vinyl), 7.05 (d, J = 12.6 Hz, 1H, vinyl), 7.30–7.37 (m, 3H, phenyl), 7.57–7.61 (m, 2H, phenyl), 11.32 (brs, 1H, CO_2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 118.66, 128.06, 129.36, 129.94, 134.32, 145.90, 171.67.

4.5. (2Z)-3-(2-Methylphenyl)propenoic acid (*o*-**2b**) and (2Z)-3-(4-methylphenyl)propenoic acid (*p*-**2b**) [31]

A mixture of *o*-**2b** and *p*-**2b** were obtained as colorless crystals. ^{1}H NMR of the crude product (300 MHz, $CDCl_3$) δ 2.28 (s, 6H, *o*-**2b** aryl-CH_3), 2.35 (s, 3H, *p*-**2b** aryl-CH_3), 5.88 (d, J = 12.8 Hz, 1H, *p*-**2b** vinyl), 6.02 (d, J = 12.3 Hz, 2H, *o*-**2b** vinyl), 7.00 (d, J = 12.8 Hz, 1H, *p*-**2b** vinyl), 7.16 (d, J = 12.3 Hz, 2H, *o*-**2b** vinyl), 7.06–7.24 (m), 7.33 (d, J = 7.7 Hz, 2H, *p*-**2b** aryl), 7.52 (d, J = 7.7 Hz, 1H, *p*-**2b** aryl). *o*- and *p*-**2b** were confirmed by GC–MS. They were also confirmed by converting them to their ethyl esters using DMAP/DCC method and comparing ^{1}H NMR spectra [9].

4.6. 3,3-Ditolylpropionic acid [32]

3,3-Ditolylpropionic acid was formed in the reaction of toluene and **1**. This was confirmed by GC–MS analysis of the product mixture and analysis of the product mixture after ethyl esterification with DMAP/DCC. ^{1}H NMR and GC–MS analyses showed that two possible isomers of 3,3-ditolylpropionic acid were formed, that is, 3,3-di(*p*-tolyl)propionic acid and 3-*p*-tolyl-3-*o*-tolylpropionic acid because (1) only *p*-**2b** underwent second hydroarylation leading to 3,3-ditolylpropionic acid, (2) the reaction of toluene and **1** gave only *o*- and *p*-**2b** without the *meta*-isomer, and (3) only two isomers of 3,3-ditolylpropionic acid were formed.

To confirm the structure of two isomers *o*- and *p*-**2b**, the independent synthesis was conducted by hydroarylation of 2- or 4-methylcinnamic acid with toluene under the conditions described in Section 4.1. The spectral data are as follows: 3-(2-Methylphenyl)-3-(4-methylphenyl)propionic acid: m.p. 113–114 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.269 (s, 3H, CH_3), 2.273 (s, 3H, CH_3), 3.01 (d, J = 7.8 Hz, 2H, CH_2), 4.67 (t, J = 7.8 Hz, 1H, CH), 7.05–7.24 (m, 8H, ArH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.72, 20.94, 40.76, 42.23, 126.14, 126350, 127.71, 129.21, 135.99, 136.21, 139.80, 141.18, 177.66 (two peaks overlapped); IR (KBr) 3400–2500 (br, OH), 1703 cm^{-1} (s, C=O). 3,3-Bis(4-methylphenyl)propionic acid: m.p. 187–188 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.28 (s, 6H, CH_3), 3.03 (d, J = 8.1 Hz, 2H, CH_2), 4.44 (t, J = 8.1 Hz, 1H, CH), 7.05–7.11 (m, 8H, ArH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 20.95, 40.42, 45.87, 127.39, 129.28, 136.06, 140.51, 177.17; IR (KBr) 3350–2500 (br, OH), 1698 cm^{-1} (s, C=O).

4.7. (2Z)-3-(2,5-Dimethylphenyl)propenoic acid (**2c**)

Colorless crystals; m.p. 100–101 °C (EtOH/hexane); ^{1}H NMR (300 MHz, CD_3OD) δ 2.22 (s, 3H, aryl-CH_3), 2.27 (s, 3H, aryl-CH_3), 5.98 (d, J = 12.3 Hz, 1H, vinyl), 7.00–7.06 (m, 2H, aryl), 7.12 (s, 1H, aryl), 7.18 (d, J = 12.3 Hz, 1H, vinyl), 11.00 (brs, 1H, CO_2H); ^{13}C NMR (75 MHz, CD_3OD) δ 19.32, 20.81, 119.82, 129.35, 129.51, 129.63, 132.72, 134.20, 134.67, 145.83, 171.43. Complex **2c** was confirmed by converting it to its ethyl ester **3d** using DMAP/DCC method and comparing ^{1}H and ^{13}C NMR spectra [5b].

4.8. (2Z)-3-(2,4,6-Trimethylphenyl)propenoic acid (**2d**) [25b]

Colorless crystals; m.p. 144–146 °C (EtOH/hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.15 (s, 6H, aryl-CH_3), 2.27 (s, 3H, aryl-CH_3), 6.10 (d, J = 12.0 Hz, 1H, vinyl), 6.84 (s, 2H, aryl), 7.11 (d, J = 12.0 Hz, 1H, vinyl), 11.00 (s, 1H, COOH); ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.00, 20.89, 122.07, 127.89, 131.99, 134.44, 136.92, 146.28, 171.10; MS (EI, m/z) 190 (M^+).

4.9. (2Z)-3-(Pentamethylphenyl)propenoic acid (**2e**) [25b]

Colorless crystals; m.p. 218–219 °C (AcOEt); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.13 (s, 6H, aryl-CH_3), 2.19 (s, 6H, aryl-CH_3), 2.22 (s, 3H, aryl-CH_3), 6.12 (d, J = 12.0 Hz, 1H, vinyl), 7.20 (d, J = 12.0 Hz, 1H, vinyl), 10.42 (brs, 1H, COOH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.35, 16.76, 17.62, 121.72, 129.87, 132.22, 132.38, 134.51, 148.28, 170.38.

4.10. (2Z)-3-(3-Bromo-2,4,6-trimethylphenyl)propenoic acid (**2f**) [25b]

Colorless powder; m.p. 148–149 °C (EtOAc/hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.10 (s, 3H, aryl-CH_3), 2.28 (s, 3H, aryl-CH_3), 2.36 (s, 3H, aryl-CH_3), 6.11 (d, J = 12.0 Hz, 1H, vinyl), 6.91 (s, 1H, aryl), 7.09 (d, J = 12.0 Hz, 1H, vinyl), 9.86 (brs, 1H, COOH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.89, 21.25, 23.93, 122.48, 125.14, 129.44, 133.16, 133.83, 134.30, 137.28, 145.97, 170.35.

4.11. (2Z)-3-(1-Naphthyl)propenoic acid (**2g**) [25b]

Slightly yellow solid; m.p. 157–158 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.21 (d, J = 12.0 Hz, 1H, vinyl) 7.39–7.53 (m, 4H, naphthyl),7.66 (d, J = 12.0 Hz, 1H, vinyl), 7.81–7.87 (m, 3H, naphthyl), 9.80 (brs, 1H, COOH); ^{13}C NMR (75 MHz, $CDCl_3$) δ 121.37, 124.18, 125.08, 125.97, 126.44, 126.92, 128.62, 129.15, 130.91, 132.27, 133.22, 144.66, 170.30; MS (EI, m/z) 198 (M^+).

4.12. (2Z)-3-(2,5-Di-tert-butylphenyl)propenoic acid (**2h**)

Colorless crystals; m.p. 152–154 °C (toluene); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.25 (s, 9H, ^{t}Butyl), 1.35 (s, 9H, ^{t}Butyl), 5.96 (d, J = 12.0 Hz, 1H, vinyl), 7.12 (d, J = 2.1 Hz, 1H, aryl), 7.25 (dd, J = 2.1, 8.1 Hz, 1H, aryl), 7.33 (d, J = 8.1 Hz, 1H, aryl), 7.72

(d, J = 12.0 Hz, 1H, vinyl), 9.43 (brs, 1H, CO_2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 30.93, 31.10, 34.15, 35.36, 118.67, 125.11, 125.54, 128.41, 134.11, 144.31, 147.84, 150.24, 171.65. Anal. Calc. for $C_{17}H_{24}O_2$: C, 78.42; H, 9.29. Found: C, 78.35; H, 9.19%.

4.13. Ethyl (2Z)-3-(2,5-dimethylphenyl)propenoate (**4a**) [5b]

Colorless liquid; ^1H NMR (300 MHz, $CDCl_3$) δ 1.14 (t, J = 7.1 Hz, 3H, CH_3), 2.23 (s, 3H, aryl-CH_3), 2.29 (s, 3H, aryl-CH_3), 4.09 (q, J = 7.1 Hz, 2H, OCH_2), 6.00 (d, J = 12.0 Hz, 1H, vinyl), 6.98–7.08 (m, 2H, aryl), 7.08 (d, J = 12.0 Hz, 1H, vinyl), 7.11 (s, 1H, aryl); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.94, 19.33, 20.88, 60.06, 120.99, 129.09, 129.26, 129.53, 132.61, 134.46, 134.87, 142.86, 166.09.

4.14. Ethyl (2Z)-3-(2,4,6-trimethylphenyl)propenoate (**4b**) [5b]

Colorless liquid; ^1H NMR (300 MHz, $CDCl_3$) δ 1.10 (t, J = 7.1 Hz, 3H, CH_3), 2.16 (s, 6H, aryl-CH_3), 2.27 (s, 3H, aryl-CH_3), 4.03 (q, J = 7.1 Hz, 2H, OCH_2), 6.11 (d, J = 12.0 Hz, 1H, vinyl), 6.84 (s, 2H, aryl), 7.02 (d, J = 12.0 Hz, 1H, vinyl); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.94, 20.11, 21.01, 59.92, 122.77, 127.78, 132.77, 134.44, 136.65, 144.13, 165.47.

4.15. Ethyl (2Z)-3-(pentamethylphenyl)propenoate (**4c**) [5b]

Colorless crystals; m.p. 72–74 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 1.10 (t, J = 7.1 Hz, 3H, CH_3), 2.14 (s, 6H, aryl-CH_3), 2.20 (s, 6H, aryl-CH_3), 2.22 (s, 3H, aryl-CH_3), 4.01 (q, J = 7.1 Hz, 2H, OCH_2), 6.13 (d, J = 12.0 Hz, 1H, vinyl), 7.12 (d, J = 12.0 Hz, 1H, vinyl); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.96, 16.36, 16.74, 17.59, 59.78, 122.13, 129.76, 131.89, 133.23, 133.95, 146.46, 165.42.

4.16. Ethyl (2Z)-3-(3-hydroxy-2,4,6-trimethylphenyl)propenoate (**4d**) [5b]

Colorless crystals; m.p. 59–60 °C (hexane); ^1H NMR (300 MHz, $CDCl_3$) δ 1.11 (t, J = 7.1 Hz, 3H, CH_3), 2.10 (s, 6H, aryl-CH_3), 2.20 (s, 3H, aryl-CH_3), 4.03 (q, J = 7.1 Hz, 2H, OCH_2), 4.49 (s, 1H, OH), 6.13 (d, J = 12.0 Hz, 1H, vinyl), 6.80 (s, 1H, aryl), 7.00 (d, J = 12.0 Hz, 1H, vinyl); ^{13}C NMR (75 MHz, $CDCl_3$) δ 12.97, 13.96, 15.85, 19.54, 59.97, 120.18, 121.86, 122.86, 126.17, 129.15, 134.31, 143.94, 149.77, 165.39.

4.17. Ethyl (2Z)-3-{3-[(1Z)-2-ethoxycarbonylethenyl]-2,4,6-trimethylphenyl}propenoate (**5a**) [5b]

Light yellow oil; ^1H NMR (300 MHz, $CDCl_3$) δ 1.12 (t, J = 7.1 Hz, 6H, CH_3), 2.05 (s, 3H, aryl-CH_3), 2.15 (s, 6H, aryl-CH_3), 4.03 (q, J = 7.1 Hz, 4H, OCH_2), 6.12 (d, J = 11.7 Hz, 2H, vinyl), 6.88 (s, 1H, aryl), 7.04 (d, J = 11.7 Hz, 2H, vinyl); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.98, 17.66, 20.17, 59.90, 122.68, 128.36, 130.97, 132.98, 133.46, 144.40, 165.38.

4.18. Ethyl (2Z)-3-{5-[(1Z)-2-ethoxycarbonylethenyl]-3-hydroxy-2,4,6-trimethylphenyl}propenoate (**5b**) [25b]

Colorless crystals; m.p. 109–112 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 1.12 (t, J = 7.1 Hz, 6H, CH_3), 1.99 (s, 3H, aryl-CH_3), 2.10 (s, 6H, aryl-CH_3), 4.03 (q, J = 7.1 Hz, 4H, OCH_2), 4.53 (s, 1H, OH), 6.14 (d, J = 12.0 Hz, 2H, vinyl), 7.02 (d, J = 12.0 Hz, 2H, vinyl); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.20, 13.98, 17.33, 59.95, 119.42, 122.87 (two peaks overlapped), 133.85, 144.24, 149.44, 165.33; MS (EI, m/z) 332 (M^+).

Acknowledgements

This work was supported by a Grant-in-Aid for Scientific Research on Priority Areas "Advanced Molecular Transformations of Carbon Resources" from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and by management expenses grants for national university corporations. J.O. thanks JSPS Research Fellowships for Young Scientists.

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