Heck-type coupling *vs.* conjugate addition in phosphine–rhodium catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyl compounds: a systematic investigation†

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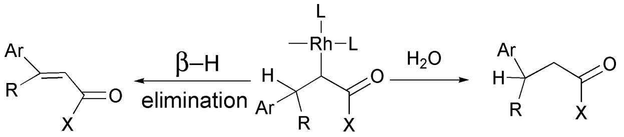
The competition between Heck-type coupling and conjugate addition in phosphine–rhodium catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyls has been systematically investigated in a toluene–H_2O biphasic system. Aside from the intrinsic nature of rhodium and the enolization of carbonyls, the phosphine supporting ligand on rhodium, the ratio of aryl boronic acid to α,β-unsaturated carbonyl and the pH value of the aqueous phase were found to affect the competition significantly. Highly selective rhodium-based catalyst systems have therefore been developed for both Heck-type coupling and conjugate addition by synergistically tuning the supporting ligand, the boronic acid to olefin ratio and other reaction conditions. Conjugate addition with selectivity >99% and Heck-type coupling with selectivity of up to 100%, 98% and 84% for acrylates, acrylamides and methyl vinyl ketone, respectively, could be achieved in the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyls using the corresponding optimized rhodium-based catalyst systems.

Introduction

The rhodium-catalyzed conjugate addition (CA) of aryl boronic acids to α,β-unsaturated carbonyl compounds is often reported as a highly selective procedure,[1] although, according to the currently accepted mechanism,[2] there is a mechanistically competitive side reaction, Heck-type coupling (HC), which results from β-H elimination of the α-rhodium carbonyl intermediates (Scheme 1).



Scheme 1 The competition of β-H elimination *vs.* hydrolysis of α-rhodium carbonyls.

Considering that the Heck-type coupling of aryl boronic acids with α,β-unsaturated carbonyl compounds is well known for non-rhodium transition metal catalysts, such as Ir, Ru and Pd, it looks reasonable to attribute the bias in favor of conjugate addition with rhodium catalysts to the intrinsic nature of rhodium metal that disfavors β-H elimination for the Heck-type coupling.[3] However, from an organometallic chemistry point of view, the reactivity of an organorhodium species is not only determined by the intrinsic nature of rhodium, but also tuned by supporting ligands and reaction conditions. That is to say the HC : CA selectivity should be tunable in the rhodium-catalyzed C–C bond forming reactions of aryl boronic acids with α,β-unsaturated carbonyls. In fact, in closely related rhodium-catalyzed reactions of aryl silicons with α,β-unsaturated esters, Heck-type coupling arose under anhydrous conditions while conjugate addition occurred favorably in the presence of water, demonstrating that the competition between hydrolysis and β-H elimination of α-rhodium carbonyls could be controlled by reaction conditions.[4] Owing to the covalent property of a Rh–C bond, the favored pathway for hydrolysis of the Rh–C bond consists of an oxidative addition–reductive elimination (OA–RE) sequence with H_2O instead of direct hydrolysis as a carbon anion.[5] The OA–RE process is strongly dependent on ligands bound to the metal, including the σ-bonded carbon group as well as the coordinatively bound supporting ligands. Thus, it is possible to coordinatively control the hydrolysis *vs.* *β*-H elimination competition of an organorhodium species. Lautens and co-workers have reported a rhodium-catalyzed Heck-type coupling of aryl boronic acids with styrene in an aqueous system,[6] proving that hydrolysis of the Rh–C could be blocked even in the presence of water. For α-rhodium carbonyls in particular, there is one more hydrolysis path, enolization–hydrolysis. Therefore, it would be more difficult to achieve rhodium-catalyzed Heck-type coupling of aryl boronic acids with α,β-unsaturated carbonyls by blocking the hydrolysis of α-rhodium carbonyls in the presence of a proton source, such as water (Scheme 2).

Fortunately, the C–metal tautomer is favored over the O–metal enolate, in the metal tautomerism of α-rhodium carbonyls owing to the soft property of the rhodium ion.[7] Therefore, there should still be a chance to control the competition between β-H elimination and hydrolysis of the α-rhodium carbonyl species even in the presence of water, especially for carbonyls with a low enolization tendency. Based on this conjecture, we attained highly selective rhodium-catalyzed Heck-type coupling of arylboronic acids with acrylates using a biphasic system of water–toluene consisting of

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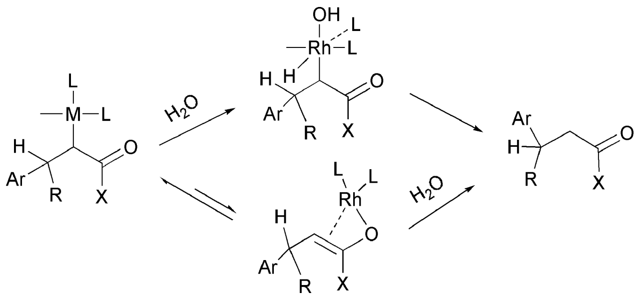


Scheme 2 Hydrolysis paths of α-rhodium carbonyls.

$RhCl_3$–PR_3 or $(PR_3)_3RhCl$ and K_2CO_3, thereby demonstrating tunability of the competition of β-H elimination *vs.* hydrolysis of α-rhodium carbonyls in the presence of water for the first time.[8] Shortly after this, a β-hydroxy elimination reaction against the hydrolysis of α-rhodium, β-hydroxy carbonyls was described to control the reaction direction in the rhodium-catalyzed reactions of boronic acids with Baylis–Hillmann adducts.[9] Recently, Lautens and co-workers have further reported the impact of steric effects of both ligands and substrates on the HC : CA selectivity in the rhodium-catalyzed reactions of aryl boronic acids with unsaturated carboxylic acid derivatives in emulsion systems.[10] Herein we report in detail our systematic investigation of the influence of phosphine ligands, carbonyls and reaction conditions on the competition of β-H elimination *vs.* hydrolysis of α-rhodium carbonyl intermediates in the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyls. This investigation allowed the development of highly selective rhodium-based catalyst systems for both the Heck-type coupling and conjugate addition for α,β-unsaturated esters, amides and ketones.

Experimental

General

All reactions were performed in N_2 atmosphere unless otherwise indicated. All commercially available chemicals were used as received. Aryl boronic acids, dppp, dppf, dppe, dppb, dppm, (±)binap and methyl vinyl ketone (MVK) were purchased from Sigma-Aldrich or Acros. Vinyl phenyl ketone was prepared according to the previously reported procedure.[11] ^1H NMR spectra were recorded on a Bruker 500 spectrometer (500 MHz) using the residue of deuterated solvent ($CDCl_3$) as the internal standard. GC/GC-MS analysis was performed using a Hewlett Packard Model HP 6890 Series with HP-5 column.

General procedure for the Heck-type coupling of aryl boronic acids with α,β-unsaturated amides and esters

To a suspension of aryl boronic acid (1.0 mmol), $RhCl_3(H_2O)_3$ (9 mg, 0.03 mmol), PPh_3 (33 mg, 0.12 mmol) and K_2CO_3 (0.45 g, 3 mmol) in toluene–water (15 ml : 5 ml) was added α,β-unsaturated amide or ester (2.0 mmol). The mixture was stirred at 120 °C (bath temperature) under nitrogen. Progress of the reaction was monitored by TLC until complete consumption of aryl boronic acid occurred. After cooling to room temperature, the organic phase of the reaction mixture was separated from the aqueous phase, concentrated and purified by column chromatography (silica gel) to afford Heck-type coupling product (or a mixture with a small amount of conjugate addition product).

General procedure for the conjugate addition of aryl boronic acids to α,β-unsaturated amides

To a suspension of aryl boronic acid (2.0 mmol), $RhCl_3(H_2O)_3$ (9 mg, 0.03 mmol) and dppp (41 mg, 0.10 mmol) in toluene–water (15 ml : 5 ml) was added α,β-unsaturated amide (1.0 mmol). The mixture was stirred at 80 °C (bath temperature) under nitrogen. Progress of the reaction was monitored by GC or TLC until complete consumption of α,β-unsaturated amide occurred. A work-up procedure similar to that for Heck-type coupling afforded conjugate addition product (or a mixture with a small amount of Heck-type coupling product).

General procedure for the conjugate addition of aryl boronic acids to α,β-unsaturated esters

To a suspension of aryl boronic acid (2.0 mmol), $RhCl_3(H_2O)_3$ (9 mg, 0.03 mmol) and (±)binap (90 mg, 0.15 mmol) in toluene–water (15 ml : 5 ml) was added α,β-unsaturated ester (1.0 mmol). The mixture was stirred at 80 °C (bath temperature) under nitrogen. Progress of the reaction was monitored by GC until complete consumption of α,β-unsaturated ester occurred. A work-up procedure similar to that for Heck-type coupling of esters afforded conjugate addition product (or a mixture with a small amount of Heck-type coupling product)

General procedure for the Heck-type coupling of aryl boronic acids with α,β-unsaturated ketones

To a suspension of aryl boronic acid (1.0 mmol) and $RhCl(PPh_3)_3$ (28 mg, 0.03 mmol) in toluene–water (15 ml : 5 ml) was added α,β-unsaturated ketone (4.0 mmol). The mixture was stirred at 120 °C (bath temperature) under nitrogen. Progress of the reaction was monitored by TLC until the complete consumption of aryl boronic acid occurred. A work-up procedure similar to that for Heck-type coupling of esters afforded the Heck-type coupling product as a mixture with the conjugate addition product.

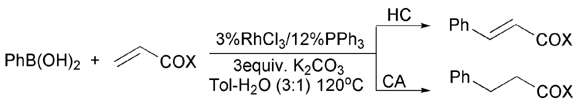
General procedure for the conjugate addition of aryl boronic acids to α,β-unsaturated ketones

To a suspension of aryl boronic acid (2.0 mmol) $RhCl_3(H_2O)_3$ (9 mg, 0.03 mmol) and (±)binap (90 mg, 0.15 mmol) in toluene–water (15 ml : 5 ml) was added α,β-unsaturated ketone (1.0 mmol). The mixture was stirred at 80 °C (bath temperature) under nitrogen. Progress of the reaction was monitored by GC until the complete consumption of α,β-unsaturated ketone occurred. A work-up procedure similar to that for Heck-type coupling afforded the conjugate addition product.

Results and discussion

In order to systematically investigate the influence of supporting ligands and reaction conditions on the competition between β-H elimination and hydrolysis of α-rhodium carbonyl intermediates, namely HC : CA selectivity, in the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyl compounds, a proper model had to be established. The reactions of phenyl

Table 1 Establishment of the model reaction



Entry	X	B : O	HC : CA[a]	Yield (%)[b]
1	OBu	1 : 2	100 : 0	86
2	NMe_2	1 : 2	95 : 5	80
3	Me	1 : 2	—	—[c]
4	OBu	2 : 1	93 : 7	66
5	NMe_2	2 : 1	53 : 47	75

[a] Determined by ^{1}H NMR; no *cis* isomer of the HC products detected. [b] Isolated yield (%). [c] Complicated mixture.

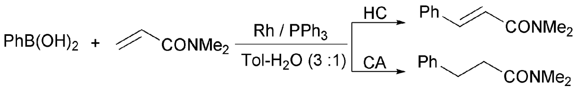
boronic acid with butyl acrylate, *N*,*N*-dimethyl acrylamide and vinyl methyl ketone (MVK), catalyzed by our previously established biphasic catalyst system of $RhCl_3$–PPh_3–K_2CO_3 in toluene–water, were screened in a parallel fashion to find the most suitable, using criteria of good chemical yield, easily monitored progress and proper HC : CA selectivity (Table 1).

The reactions of both butyl acrylate and *N*,*N*-dimethyl acrylamide proceeded cleanly while the reaction of MVK gave a complicated mixture. However, the HC : CA selectivity in the reaction of *N*,*N*-dimethyl acrylamide was sensitive to the ratio of boronic acid (B) to olefin (O), decreasing from 95 : 5 to 53 : 47 with the B : O ratios increasing from 1 : 2 to 2 : 1 (mol) (Table 1, entries 2 and 5). Meanwhile the HC : CA selectivity in the reaction of butyl acrylate consistently and overwhelmingly favored the Heck-type coupling regardless of the B : O ratios (Table 1, entries 1 and 4). Obviously, the competition between β-H elimination and hydrolysis of α-rhodium amides is easier to tune than that of esters. Thus, the reaction of *N*,*N*-dimethyl acrylamide with phenyl boronic acid was chosen as the model. The influence of reaction conditions on the HC : CA selectivity was investigated at first and the results are compiled in Table 2.

When *N*,*N*-dimethyl acrylamide was used in excess (2 and 4 equiv.), the Heck-type coupling proceeded with high selectivity to the conjugate addition using 3% $RhCl_3$–12% PPh_3 as a catalyst in the presence of 3 equiv. K_2CO_3, (Table 2, entries 1 and 2). The beneficial effects of excess terminal olefin used in Heck-type coupling reactions have been reported to originate from the consumption of the Rh–H species generated from β-H elimination.[4] However, even when an equivalent amount of *N*,*N*-dimethyl acrylamide was used the HC : CA selectivity was still as high as 92 : 8 with 60% overall yield (Table 2, entry 11), supporting the existence of alternative routes for the conversion of Rh–H species into Rh–Ar.

Basic conditions looked to be crucial to the β-H elimination of α-rhodium amides. For example, the HC : CA selectivity reversed from favoring Heck-type coupling in the presence of K_2CO_3, to favor conjugate addition (20 : 80) in the absence of K_2CO_3, although the reaction became much slower giving only a 32% yield after 30 h (Table 2, entries 1 and 3). Since the 3% $RhCl_3$–12% PPh_3 system is assumed to work through *in situ* formation of Rh(I) species, *e.g.* $RhCl(PPh_3)_3$, the decrease of reaction rate could be attributed to the difficulty in the formation of Rh(I) species in the absence of base. In fact, when the Wilkinson catalyst, $RhCl(PPh_3)_3$, was used in place of 3% $RhCl_3$–12% PPh_3 the reaction rate did improve, but the HC : CA selectivity was poor (Table 2, entry 4), implying differences between the $RhCl_3$–PPh_3 system and the Wilkinson catalyst.[12] However, in the presence of K_2CO_3, the HC : CA selectivity with $RhCl(PPh_3)_3$ compared favorably to that obtained with the combination of 3% $RhCl_3$ and 12% PPh_3, confirming the necessity of a basic condition for β-H elimination

Table 2 HC : CA selectivity in the model reaction of acrylamide with phenyl boronic acid under various conditions



Entry	B : O	Catalyst	Base[a]	T/°C	t/h	HC : CA[b]	Yield (%)[c]
1	1 : 2	3% $RhCl_3$–12% PPh_3	K_2CO_3	120	5	95 : 5	78
2	1 : 4	3% $RhCl_3$–12% PPh_3	K_2CO_3	120	5	98 : 2	80
3	1 : 2	3% $RhCl_3$–12% PPh_3	—	120	30	20 : 80	32
4	1 : 2	3% $RhCl(PPh_3)_3$	—	120	5	51 : 49	73
5	1 : 2	3% $RhCl(PPh_3)_3$	K_2CO_3	120	5	93 : 7	79
6	1 : 2	3% $RhCl(PPh_3)_3$	K_2CO_3	80	8	86 : 14	86
7[d]	1 : 2	3% $RhCl(PPh_3)_3$	NH_4Cl	120	48	42 : 58	70
8	1 : 2	3% $RhCl(PPh_3)_3$	$B(OH)_3$	120	5	33 : 67	60
9[e]	1 : 2	3% $RhCl(PPh_3)_3$–PPh_3	—	120	5	40 : 60	78
10[f]	1 : 2	3% $RhCl_3$–12% PPh_3	K_2CO_3	120	5	96 : 4	71
11	1 : 1	3% $RhCl_3$–12% PPh_3	K_2CO_3	120	8	92 : 8	60
12	2 : 1	3% $RhCl_3$–12% PPh_3	K_2CO_3	120	5	55 : 45	80
13	2 : 1	3% $RhCl_3$–30% PPh_3	K_2CO_3	120	5	31 : 69	77
14	2 : 1	3% $RhCl_3$–12% PPh_3	—	120	30	6 : 94	43
15	2 : 1	3% $RhCl_3$–12% PPh_3	—	80	48	8 : 92	61
16	2 : 1	3% $RhCl_3$–30% PPh_3	—	80	48	8 : 92	76
17	2 : 1	3% $RhCl(PPh_3)_3$	—	80	5	16 : 84	70
18[e]	2 : 1	3% $RhCl(PPh_3)_3$–PPh_3	—	80	5	4 : 96	86

[a] 3equiv. used. [b] Determined by ^{1}HNMR; no *cis* isomer of HC product detected. [c] Isolated yield (%). [d] Saturated NH_4Cl(aq.). [e] 15% PPh_3 added. [f] Run in air.

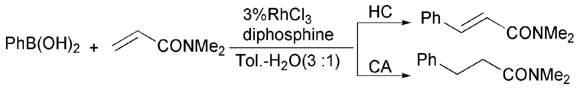
of α-rhodium amides (Table 2, entries 5 and 6). In comparison to the HC : CA selectivity obtained under neutral conditions, further lowering the pH value of the aqueous phase by using NH_4Cl or $B(OH)_3$ (3 equiv.) solution just slightly increases the conjugate addition selectivity (Table 2, entries 4, 7 and 8). Lower reaction temperature increased the overall yield, but decreased the HC : CA selectivity slightly (Table 2, entry 6). Although most of the experiments were conducted in N_2 atmosphere, a similar result with respect to both yield and HC : CA selectivity could also be obtained in air (Table 2, entry 10).

The dependence of the HC : CA selectivity on the B : O ratio and the pH value of the aqueous phase in the reaction of phenyl boronic acid with *N*,*N*-dimethyl acrylamide was further confirmed by experiments using excess phenyl boronic acid. The HC : CA selectivity decreased to 55 : 45 with excess (2 equiv.) phenyl boronic acid from 95 : 5 with excess olefin (2 equiv.), even in the presence of 3 equiv. K_2CO_3 which was found to be beneficial to Heck-type coupling (Table 2, entries 1 and 12). Furthermore, in the absence of K_2CO_3, the CA selectivity increased to 94 : 6 with excess phenyl boronic acid (2 equiv.) from 80 : 20 with excess *N*,*N*-dimethyl acrylamide (2 equiv.) (Table 2, entries 3 and 14). Again, lower reaction temperature showed a beneficial effect on the overall yields. Although the CA selectivity did not further increase, the chemical yield of the model reaction increased from 61% to 76% upon increasing the PPh_3 loading from 12% to 30% (mol) (Table 2, entries 15 and 16). Using the Wilkinson catalyst, $RhCl(PPh_3)_3$, in place of the direct combination of 3% $RhCl_3$ and 12% PPh_3, gave slightly lower CA selectivity. But good CA selectivity could be restored by using extra PPh_3 along with $(PPh_3)_3RhCl$, which was expected to depress the β-H elimination of the α-rhodium carbonyl intermediate (Table 2, entries 17 and 18). Based on these experiments, it could be concluded that basic aqueous, excess olefin and higher temperature promote the β-H elimination while non-basic conditions, excess aryl boronic acid and lower temperature benefit hydrolysis of α-rhodium amides. That is to say the HC : CA selectivity in the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated amides could be tuned by properly choosing reaction conditions.

It is reasonable to anticipate that the chelate effects of bidentate phosphine ligands could increase the CA selectivity since they depress the formation of a coordinatively unsaturated rhodium species, thus slowing down the β-H elimination for Heck-type coupling. Therefore, diphosphine ligands, 1,1′-bis(diphenylphosphino)ferrocene (dppf), 1,1-bis(diphenylphosphino)methane (dppm), 1,2-bis(diphenylphosphino)ethane (dppe), 1,4-bis(diphenylphosphino)butane (dppb), 1,3-bis(diphenylphosphino)propane (dppp) and (±)2,2′-bis(diphenylphosphino)-1,1′-binaphthalene (binap), were tested in the model reaction of phenyl boronic acid with *N*,*N*-dimethyl acrylamide under the optimized conditions for Heck-type coupling and conjugate addition, respectively (Table 3).

As expected, the CA selectivity in the model reaction upon using diphosphines increased compared to the same reaction with PPh_3 under otherwise identical conditions. The structure of diphosphine showed remarkable influence on both the chemical yields and CA : HC selectivity. In the absence of K_2CO_3, the CA product was obtained in excellent selectivity and yield with large bite angle diphosphines, dppf (98.74°), dppp (91.56°), dppb (97.07°) and binap (92.77°), using just a slight excess (1.2 equiv.) of phenyl boronic acid; while both the yields and CA selectivity were comparatively low with small bite angle diphosphines, dppm (71.53°) and dppe (82.55°) (Table 3, entries 3, 5, 7, 9, 11 and 13).[13,14] Even under conditions favoring Heck-type coupling, the CA selectivity with diphosphines noticeably increased compared with that using PPh_3, except for dppm, which performed similarly to PPh_3 (Table 3, entries 1, 4, 6, 8 and 10). It is noteworthy that when binap was used as the supporting ligand for rhodium, the CA product was obtained in high yield and selectivity, regardless of the reaction conditions, B : O ratio, pH value and temperature (80–120 °C) (Table 3, entries 12 and 13). For example, the CA : HC selectivity reached 97 : 3 with a 91% yield using 2 equiv. *N*,*N*-dimethyl acrylamide, 3% $RhCl_3$, 6% binap and 3 equiv. K_2CO_3,

Table 3 Chelate effects of diphosphines on the HC : CA selectivity in the model reaction



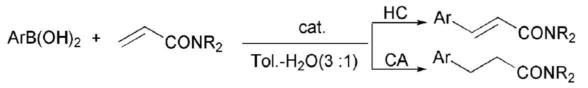
Entry	B : O	Phosphine	Base[a]	T/°C	t/h	HC : CA[b]	Yield (%)[c]
1	1 : 2	6% dppf	K_2CO_3	120	5	81 : 19	96
2	2 : 1	10% dppf	—	80	10	0 : 100	93
3	1.2 : 1	10% dppf	—	80	10	1 : 99	92
4	1 : 2	6% dppe	K_2CO_3	120	25	55 : 45	17
5	1.2 : 1	10% dppe	—	80	70	21 : 79	65
6	1 : 2	6% dppm	K_2CO_3	120	20	92 : 8	83
7	1.2 : 1	10% dppm	—	80	70	25 : 75	18
8	1 : 2	6% dppp	K_2CO_3	120	25	61 : 39	86
9	1.2 : 1	10% dppp	—	80	10	0 : 100	93
10	1 : 2	6% dppb	K_2CO_3	120	5	77 : 23	93
11	1.2 : 1	10% dppb	—	80	10	4 : 96	91
12	1 : 2	6% binap	K_2CO_3	120	5	3 : 97	91
13	1.2 : 1	10% binap	—	80	15	2 : 98	93
14	1.2 : 1	3% binap	—	80	30	3 : 97	93
15	1.2 : 1	6% dppp	—	80	10	2 : 98	94
16	1.2 : 1	3% dppp	—	80	20	20 : 80	66

[a] 3equiv. used. [b] Determined by ^{1}H NMR; no *cis* isomer of HC product detected. [c] Isolated yield (%).

conditions that were found to disfavor conjugate addition for the other tested phosphine ligands, especially PPh_3, with which high HC : CA selectivity (95 : 5) was obtained. Since binap has a comparable bite angle and the same diphenyl phosphine units as dppp, it is clear that the HC : CA selectivity in the rhodium-catalyzed process is also affected by the rigidness of the chelate ligands. Decrease of the ratio of diphosphine to Rh markedly decreased the reaction rate and even the CA selectivity with some ligands, such as dppp, resembling the results obtained with PPh_3. For example, using 3% $RhCl_3$ at 80 °C, a longer reaction time was required for the reaction to go to completion — 3% binap loading (30 h) compared to 10% loading (15 h) —although the CA selectivity and yields remained unchanged (Table 3, entries 13 and 14). The conjugate addition of $PhB(OH)_3$ (1.2 equiv) to *N*,*N*-dimethyl acrylamide went to completion within 10 h giving 93% yield and 100% CA selectivity with 10% dppp and 3% $RhCl_3$ (Table 3, entry 9). However, when the dppp loading was reduced to 3% both the CA : HC selectivity and yield decreased significantly to 80 : 20 and 66%, respectively, with longer reaction time (Table 3, entry 16). These results indicated that phosphine ligands play an important role in the formation and reactivity of α-rhodium amides.

Electronic effects of the boronic acid aryl group on the HC : CA selectivity in the reactions with acrylamides were also investigated and the results are listed in Table 4. Clearly, electronic effects from aryl boronic acids on both Heck-type coupling and conjugate addition were negligible. For example, under conditions favoring conjugate addition with dppp as the ligand, all the tested aryl boronic acids, including *p*-methoxy and *p*-acetyl phenyl boronic acids, reacted to provide CA products with >99% selectivity (Table 4, entries 1, 2, 4, 6 and 8). Heck-type coupling also proceeded with high HC : CA selectivity ranging from 85 : 15 for 3,5-bis(trifluoromethyl)phenyl boronic acid to 99 : 1 for *p*-methoxy and *p*-acetyl phenyl boronic acids under the HC-favored conditions (Table 4, entries 3, 5, 7 and 9). The poor yields in the reactions of 3,5-bis(trifluoromethyl)phenyl boronic acid may be attributed to deboronation since 1,3-bis(trifluoromethyl) benzene was detected as a component in the product mixtures.

Table 4 Electronic effects of aryl boronic acids on the HC : CA selectivity in the reactions with acrylamides



Entry	Ar	R	Cond.[a]	t/h	HC : CA[b]	Yield (%)[c]
1	*p*-$CH_3C_6H_4$	CH_3	A	5	0 : 100	90
2	*p*-$CH_3OC_6H_4$	CH_3	A	5	0 : 100	93
3	*p*-$CH_3OC_6H_4$	CH_3	B	5	98 : 2	79
4	*p*-$CH_3COC_6H_4$	CH_3	A	6	<1 : 99	71
5	*p*-$CH_3COC_6H_4$	CH_3	B	7	>99 : 1	73
6	Ph	H	A	6	<1 : 99	90
7	Ph	H	B	6	91 : 9	69
8	3,5-$(CF_3)_2C_6H_3$	CH_3	A	6	<1 : 99	43
9	3,5-$(CF_3)_2C_6H_3$	CH_3	B	7	85 : 15	49

[a] A: Boronic acid : olefin = 1.2 : 1 (mol), L = dppp (10% mol), 80 °C; B: Boronic acid : olefin = 1 : 2, L=PPh_3 (12% mol), 3equiv. K_2CO_3, 120 °C. [b] Determined by ^1H NMR; no *cis* isomer of HC products detected. [c] Isolated yield (%).

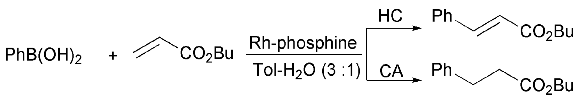
Unlike the aryl group, the carbonyl moiety can coordinate with the rhodium ion and is the root of enolization of the α-rhodium β-aryl carbonyl intermediate, thus significantly affecting the β-H elimination *vs.* hydrolysis competition. In fact, during our screening for the model reaction, the HC : CA selectivity in the reaction of butyl acrylate with phenyl boronic acid was found to be less sensitive to the B : O ratio than that of acrylamide (see Table 1). Thus, the tunability of the hydrolysis *vs. β*-H elimination competition of α-rhodium ester intermediates in the reactions of aryl boronic acids with α,β-unsaturated esters, was explored using the reaction of butyl acrylate as the model (Table 5).

In sharp contrast to results obtained with α,β-unsaturated amides, the pH value of the aqueous phase and B : O ratio showed few effects on the HC : CA selectivity in the reaction of butyl acrylate with phenyl boronic acid catalyzed by the Rh–PPh_3 toluene–water system. The HC : CA selectivity is consistently high (98% or higher) with excess (2 equiv.) butyl acrylate albeit the yields and reaction rate varied with the change of reaction conditions (Table 5, entries 1–4). Even with excess phenyl boronic acid (2–4 equiv.), the Heck-coupling was still favored (Table 5, entries 5 and 6). These results clearly indicated that the carbonyl structures could significantly affect the β-H elimination *vs.* hydrolysis competition of the α-rhodium carbonyls. With the stronger donating ligand tricyclohexyl phosphine, PCy_3, the CA selectivity increased significantly, but the Heck-type coupling was still favored (Table 5, entries 7 and 8).

The chelate effects of most of the bidentate phosphine ligands on the HC : CA selectivity were smaller in the reaction of butyl acrylate than those observed with acrylamides under similar conditions. For example, the CA selectivity increased to 20–45% with bidentate ligands of dppm, dppe, dppf, dppb and dppp using 2 equiv. phenyl boronic acid without K_2CO_3, while the Heck-type coupling still proceeded with >92% selectivity with bidentate ligands dppm, dppf, dppb and dppp, except for dppe, with excess (2 equiv.) butyl acrylate and 3 equiv. K_2CO_3 (Table 5, entries 9–18). These were obviously different to the selectivities observed in the reactions of acrylamides (see Table 3). However, similar to the reactions of acrylamides, when binap was used as the supporting ligand for rhodium, the CA product was obtained in high selectivity and yields under both the HC- and CA-favored conditions (Table 6, entries 19–22). For example, 92 : 8 CA : HC selectivity and 85% yield were observed in the reaction of $PhB(OH)_2$ with excess acrylate (2 equiv.), in the presence of 3% $RhCl_3$, 6% binap and 3 equiv. K_2CO_3. The CA : HC selectivity further increased to 99 : 1 using excess phenyl boronic acid (2 equiv.) in the absence of K_2CO_3 at 80 °C. When the loading of binap was decreased from 15% to 3–6% mol, the reaction became slower albeit the CA selectivity and yields were not markedly affected (Table 6, entries 21–24).

Since esters and amides display comparable enolization tendencies, the rationale for the comparatively lower tendency of α,β-unsaturated esters than the corresponding amides towards conjugate addition may lie in the lower rhodium coordinating capability of O compared to N. The coordination of N to Rh would disfavor the β-H elimination in the α-rhodium carbonyl form and enhance the enolization by formation of chelating structure in the enolate form, thus increasing the tendency to conjugate addition (Scheme 3).

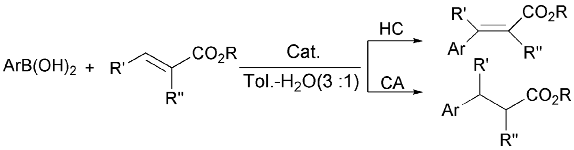
Table 5 HC : CA selectivity in the reaction of butyl acrylate with phenyl boronic acid under various conditions[a]



Entry	B : O	Catalyst	Base[b]	T/°C	t/h	HC : CA[c]	Yield (%)[d]
1	1 : 2	3% RhCl$_3$–12% PPh$_3$	K$_2$CO$_3$	120	5	100 : 0	85
2	1 : 2	3% RhCl$_3$–12% PPh$_3$	—	120	20	100 : 0	89
3	1 : 2	3% RhCl(PPh$_3$)$_3$	—	120	6	99 : 1	90
4[e]	1 : 2	3%RhCl(PPh$_3$)$_3$	NH$_4$Cl	120	48	98 : 2	78
5	2 : 1	3% RhCl$_3$–12% PPh$_3$	—	80	20	91 : 9	63
6	4 : 1	3% RhCl(PPh$_3$)$_3$	K$_2$CO$_3$	80	8	74 : 26	75
7	1 : 2	3% RhCl$_3$–12% PCy$_3$	K$_2$CO$_3$	120	3	70 : 30	80
8	2 : 1	3% RhCl$_3$–30% PCy$_3$	—	80	10	55 : 45	54
9	1 : 2	3% RhCl$_3$–6% dppf	K$_2$CO$_3$	120	5	97 : 3	89
10	2 : 1	3% RhCl$_3$–15% dppf	—	80	10	67 : 33	68
11	1 : 2	3% RhCl$_3$–6% dppm	K$_2$CO$_3$	120	6	92 : 8	55
12	2 :1	3% RhCl$_3$–15% dppm	—	80	20	80 : 20	30
13	1 : 2	3% RhCl$_3$–6% dppe	K$_2$CO$_3$	120	25	73 : 27	35
14	2 : 1	3% RhCl$_3$–15% dppe	—	80	25	55 : 45	20
15	1 : 2	3% RhCl$_3$–6% dppp	K$_2$CO$_3$	120	6	93 : 7	81
16	2 : 1	3% RhCl$_3$–15% dppp	—	80	25	60 : 40	40
17	1 : 2	3% RhCl$_3$–6% dppb	K$_2$CO$_3$	120	6	93 : 7	91
18	2 : 1	3% RhCl$_3$–15% dppb	—	80	10	55 : 45	69
19	1 : 2	3% RhCl$_3$–6% binap	K$_2$CO$_3$	120	5	8 : 92	85
20	2 : 1	3% RhCl$_3$–15% binap	—	80	10	1 : 99	89
21	1.5 : 1	3% RhCl$_3$–15% binap	—	80	15	4 : 96	91
22	2 : 1	3% RhCl$_3$–15% binap	K$_2$CO$_3$	80	20	2 : 98	95
23	2 : 1	3% RhCl$_3$–6% binap	—	80	30	2 : 98	96
24	2 : 1	3% RhCl$_3$–3% binap	—	80	36	3 : 97	89

[a] See ESI for more data on screening the reaction condition.† [b] 3 equiv. used. [c] Determined by ^{1}H NMR; no *cis* isomer of HC product detected. [d] Isolated yield (%). [e] Saturated NH$_4$Cl (aq.) used.

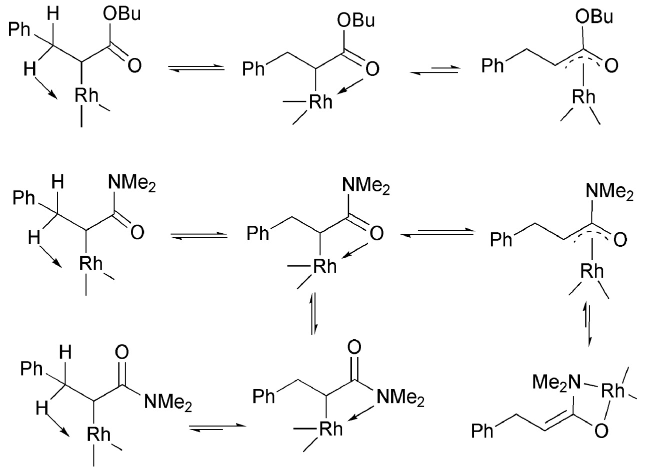
Table 6 Influence of substrate structures on the HC : CA selectivity in reactions of acrylates with aryl boronic acids



Entry	Ar	R/R′/R″	Cond.[a]	t/h	HC : CA[b]	Yield (%)[c]
1	p-CH$_3$C$_6$H$_4$	Bu/H/H	B	4	100 : 0	89
2	p-CH$_3$OC$_6$H$_4$	Bu/H/H	B	4	100 : 0	90
3	p-CH$_3$OC$_6$H$_4$	Bu/H/H	C	12	0 : 100	96
4	p-CH$_3$COC$_6$H$_4$	Bu/H/H	B	5	99 : 1	70
5	p-CH$_3$COC$_6$H$_4$	Bu/H/H	C	15	0 : 100	95
6	3,5-(CF$_3$)$_2$C$_6$H$_3$	Bu/H/H	B	6	96 : 4	65
7	3,5-(CF$_3$)$_2$C$_6$H$_3$	Bu/H/H	C	12	25 : 75	27
8	Thiophene-3	Bu/H/H	B	4	99 : 1	48
9	Thiophene-3	Bu/H/H	C	12	0 : 100	67
10	Ph	Me/H/H	B	5	100 : 0	78
11	Ph	Me/H/Me	B	15	95 : 5	18
12	Ph	Me/H/Me	C	30	0 : 100	65
13	Ph	Et/Me/H	B	18	37 : 63	21
14	Ph	Et/Me/H	C	30	0 : 100	78

[a] B: Boronic acid : olefin = 1 : 2, L = PPh$_3$ (12% mol), 3 equiv. K$_2$CO$_3$, 120 °C; C: Boronic acid : olefin = 1.2 : 1 (mol), L = binap (10% mol), 80 °C. [b] Determined by ^{1}H NMR; no *cis* isomer of HC products detected. [c] Isolated yield (%).

As with amides, the electronic effects of aryl moieties on the β-H elimination *vs.* hydrolysis competition of α-rhodium esters were negligible in most cases. High HC selectivity was consistently obtained for the reactions of both electron-rich and -poor aryl boronic acids under the HC-favored conditions (Table 6, entries 1, 2, 4 and 6). Both electron-rich and -poor aryl boronic acids, *p*-methoxy and *p*-acetyl phenyl boronic acids offered conjugate addition products in excellent yields and selectivity under the optimized conditions for the conjugate addition using binap (Table 6, entries 3 and 5), except for 3,5-bis(trifluoromethyl) phenyl boronic



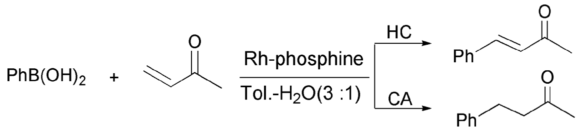
Scheme 3 Rationale for the increased tendency to conjugate addition of α,β-unsaturated amides compared to esters.

acid which gave lower HC : CA selectivity (25 : 75) and poor yield (27%) due to deboronation (Table 6, entry 7). Thiophene-3-boronic acid also provided Heck-type coupling and conjugate addition products with excellent selectivity in modest yields under HC- and CA-favored conditions, respectively (Table 6, entries 8 and 9) while complete deboronation occurred for thiophene-2-boronic acid under both sets of conditions. The β-methyl substituted α,β-unsaturated ester, crotonate, gave the conjugate addition product as the major product even under HC-favored conditions; while the α-methyl α,β-unsaturated ester, methyl methacrylate, still favored the Heck-type coupling (95 : 5) albeit the reaction became slower than with the unsubstituted acrylate (Table 6, entries 11 and 13). Not surprisingly, the CA selectivity for the reactions of both crotonate and methyl methacrylate under the CA-favored condition was exclusive (Table 6, entries 12 and 14). Besides the selectivity, the chemical yields in the conjugate addition were also much better than those in the Heck-type coupling for substituted α,β-unsaturated esters, consistent with the sensitivity of Heck-type coupling to steric hindrance of olefins.

Due to the ready enolization of ketones, rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated ketones which gave exclusively conjugate addition products were previously reported.[1,10] Encouraged by the observation of the substantial effects of supporting ligands and reaction conditions on the β-H elimination *vs.* hydrolysis competition of the α-rhodium carbonyl intermediates in the Rh-catalyzed reactions of aryl boronic acids with α,β-unsaturated esters and amides, we further explored the possibility to effect rhodium-catalyzed Heck-type coupling of α,β-unsaturated ketones with aryl boronic acids using the reaction of methyl vinyl ketone (MVK) with phenyl boronic acid as a model. Considering that MVK was unstable under basic (K_2CO_3) conditions for the reactions of α,β-unsaturated esters and amides, non-basic conditions were used. To our surprise, Heck-type coupling occurred with good HC selectivity and overall yields using the Wilkinson catalyst, $(PPh_3)_3RhCl$, in the toluene–water biphasic system. Similar to α,β-unsaturated esters and amides, the dependence of the HC : CA selectivity on the B : O ratio was again observed in the reaction of MVK (Table 7).

Using equivalent to excess MVK, Heck-type coupling occurred with HC : CA selectivity varying from 46 : 54 (1 equiv. MVK) to 73 : 27 (2 equiv. MVK) and 84 : 16 (4 equiv. MVK). However, the HC selectivity did not significantly increase further with 8 equiv. MVK (Table 7, entries 1–4). However, exclusive conjugate addition was observed when 2 equiv. phenyl boronic acid was used under otherwise identical conditions. A similar result was obtained with respect to both HC : CA selectivity and chemical yield using the combination of $RhCl_3$ and PPh_3 in place of $RhCl(PPh_3)_3$ although the reaction rate decreased (Table 7,entries 5 and 6). Chelate effects of diphosphines were also observed in the competition between β-H elimination and hydrolysis of the α-rhodium ketone. The conjugate addition occurred favorably with all tested diphosphines

Table 7 HC : CA selectivity in the reaction of phenyl boronic acid with MVK under various conditions



Entry	B : O	Catalyst	T/°C	t/h	HC : CA[a]	Yield (%)[b]
1	1 : 2	3% $RhCl(PPh_3)_3$	120	15	73 : 27	89
2	1 : 4	3% $RhCl(PPh_3)_3$	80	15	84 : 16	94
3	1 : 8	3% $RhCl(PPh_3)_3$	80	15	87 : 13	93
4	1 : 1	3% $RhCl(PPh_3)_3$	80	15	46 : 54	58
5	2 : 1	3% $RhCl(PPh_3)_3$	80	15	0 : 100	56
6	2 : 1	3% $RhCl_3$–20% PPh_3	80	36	0 : 100	55
7	1 : 4	3% $RhCl_3$–6% dppf	120	24	1 : 99	65
8	1 : 4	3% $RhCl_3$–6% dppe	120	24	30 : 70	38
9	1 : 4	3% $RhCl_3$–6% dppb	120	24	1 : 99	75
10	1 : 4	3% $RhCl_3$–6% dppm	120	24	39 : 61	46
11	1 : 4	3% $RhCl_3$–6% dppp	120	24	1 : 99	75
12	1 : 4	3% $RhCl_3$–6% binap	120	24	0 : 100	51
13	1 : 1	3% $RhCl_3$–15% binap	80	36	1 : 99	56
14[c]	2 : 1	3% $RhCl_3$–15% binap	80	36	0 : 100	84

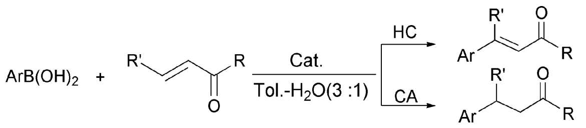
[a] Determined by ^{1}H NMR; no *cis* isomer of HC product detected. [b] Isolated yield (%). [c] Use of dppf, dppm, dppe, dppb and dppp as the supporting ligand also gave exclusive conjugate addition product but in much lower yields (11–31% by GC), see ESI for data in detail.†

regardless of the B : O ratios. The bite angle effects of chelating diphosphine ligands on the HC : CA selectivity were also remarkable. Although the conjugate addition was favored, the Heck-type coupling product was observed with 30–39% selectivity using excess olefin (4 equiv. MVK) with bidentate ligands having small bite angles, dppm (71.53°) and dppe (82.55°) (Table 7, entries 8 and 10). However, high CA selectivity (>99%) was obtained with bidentate ligands having large bite angles, dppf (98.74°), dppp (91.56°), dppb (97.07°) and binap (92.77°) under otherwise identical conditions (Table 7, entries 7, 9, 11 and 12). It has to be pointed out that the structural influence of the bidentate phosphine ligands on the HC : CA selectivity was only observed with excess MVK (4 equiv.). Using excess boronic acid (2 equiv.) the conjugate addition product was obtained exclusively in various yields.

The influence of structures of aryl boronic acids and α,β-unsaturated ketones on the β-H elimination *vs.* hydrolysis competition of the α-rhodium ketone intermediates was also investigated (Table 8). Under the CA-favored condition, conjugate addition products were obtained in >99 : 1 CA : HC selectivity in all the reactions of the tested aryl boronic acids with MVK, such as *p*-methyl, *p*-methoxy and *p*-acetyl phenyl boronic acids (Table 8, entries 2, 4 and 8). The heterocyclic boronic acid, thiophene-3-boronic acid, also reacted similarly to the phenyl analogues, giving exclusively conjugate addition product in 73% yield (Table 8, entry 10). The conjugate addition of phenyl boronic acid to phenyl vinyl ketone (PVK) and 2-cyclohexen-1-one (CEO) also occurred with exclusive CA selectivity and modest yields (Table 8, entries 14 and 16). Under the HC-favored conditions, the reactions of *p*-methyl and *p*-methoxy phenyl boronic acids with MVK showed HC : CA selectivity comparable to that of phenyl boronic acid (Table 8, entries 1 and 3). Thiophene-3-boronic acid even displayed the highest HC selectivity (90 : 10) with 70% yield (Table 8, entry 9). These results indicated that the aryl electron-donating groups exerted little influence on the competition between β-H elimination and hydrolysis of the α-rhodium ketones. However, *p*-acetyl phenyl boronic acid gave a near 1 : 1 mixture of Heck-type coupling and conjugate addition products in repeated runs under the HC-favored condition with 3–6 equiv. MVK (Table 8, entry 5). To investigate whether or not an electron-withdrawing or carbonyl group on the phenyl moiety would affect the β-H elimination of the corresponding α-rhodium ketones, the reactions of *p*-fluoro and *p*-methoxycarbonyl phenyl boronic acids were conducted under otherwise identical conditions. However, both displayed better HC : CA selectivity than *p*-acetyl phenyl boronic acid (Table 8, entries 6 and 7). The reason for the loss of selectivity in the reaction of *p*-acetyl phenyl boronic acid is not clear at present.

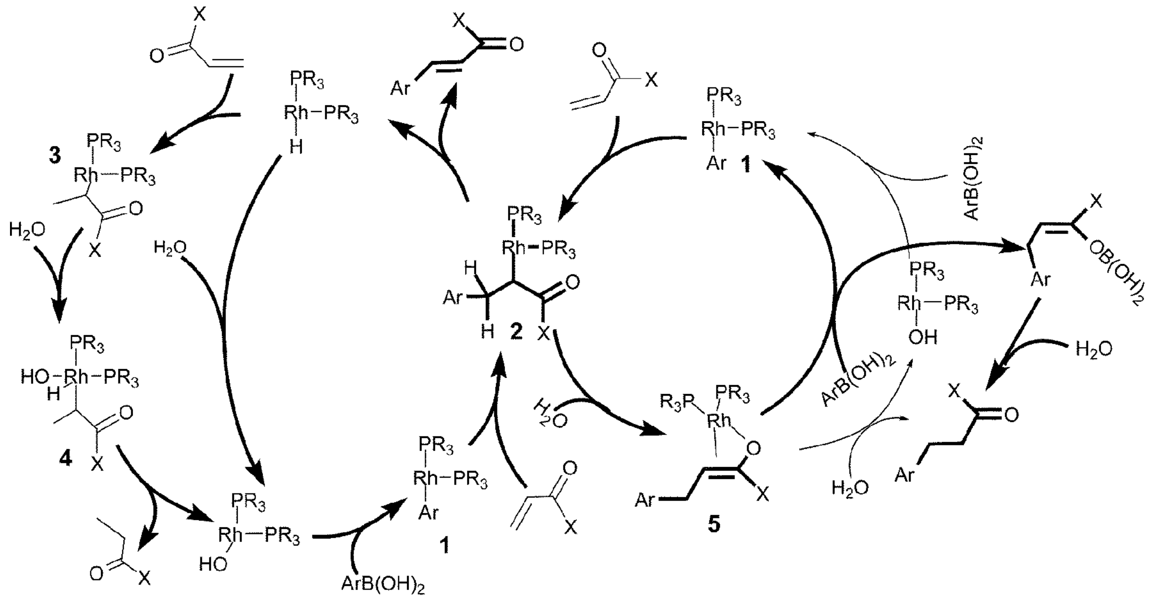
Considering that basic conditions (aq. K_2CO_3) have been found to favor Heck-type coupling in the reactions of α,β-unsaturated esters and amides and the instability of MVK to K_2CO_3(aq.), phenyl vinyl ketone (PVK) was used to explore if the presence of K_2CO_3 could increase HC selectivity in the reactions of α,β-unsaturated ketones with aryl boronic acids catalyzed by $(PPh_3)_3RhCl$ in the toluene–water biphasic system. The HC selectivity in the reaction of PVK was lower than that of MVK, consistent with the stronger enolization tendency of the α-rhodium ketone resulting from PVK than that from MVK. However, almost no change of HC : CA selectivity was observed for the reactions of PVK in the presence of 3 equiv. K_2CO_3 (Table 8, entries 11–13). Probably due to the depression of the β-substituent to β–H elimination of the α-rhodium ketone intermediate, conjugate addition was still favored even with excess cyclohexen-1-one (CEO) albeit the yield was very poor. No reaction was observed for benzylidene acetone under Heck-type coupling conditions.[15] By effecting rhodium-catalyzed Heck-type coupling of aryl boronic acids with α,β-unsaturated ketones, it is further confirmed that the competition between

Table 8 Influence from substrate structures on the HC : CA selectivity in the reactions of α,β-unsaturated ketones with aryl boronic acids



Entry	Ar	Olefin	Cond.[a]	*t*/h	HC : CA[a]	Yield (%)[c]
1	*p*-$CH_3C_6H_4$	MVK	D	20	80 : 20	93
2	*p*-$CH_3C_6H_4$	MVK	E	50	0 : 100	80
3	*p*-$CH_3OC_6H_4$	MVK	D	15	73 : 27	88
4	*p*-$CH_3OC_6H_4$	MVK	E	40	0 : 100	83
5[d]	*p*-$CH_3COC_6H_4$	MVK	D	12	49 : 51	87
6	*p*-$CH_3CO_2C_6H_4$	MVK	D	12	77 : 23	89
7	*p*-FC_6H_4	MVK	D	12	71 : 29	83
8	*p*-$CH_3COC_6H_4$	MVK	E	40	1 : 99	91
9	Thiophene-3	MVK	D	10	90 : 10	70
10	Thiophene-3	MVK	E	40	0 : 100	73
11	Ph	PVK	D	25	47 : 53	79
12	Ph	PVK	D[e]	20	43 : 57	80
13	Ph	PVK	D[e,f]	20	47 : 53	85
14	Ph	PVK	E	40	0 : 100	52
15	Ph	CEO	D	40	25 : 75	<10
16	Ph	CEO	E	40	0 : 100	65

[a] D: 3% $Rh(PPh_3)_3Cl$, 4 equiv. olefin, in toluene : H_2O (3 : 1, v/v), 120 °C; E: 3% $RhCl_3$-15% (±)-binap, 2 equiv. aryl boronic acid, in toluene : H_2O (3 : 1, v/v), 80 °C. [b] Determined by ^1H NMR; no *cis* isomer of HC products detected. [c] Isolated yield (%). [d] The reaction was repeated 3 times giving HC : CA selectivity 45 : 55, 52 : 48, 49 : 51. [e] In the presence of 3 equiv. K_2CO_3. [f] 8 equiv. PVK used.



Scheme 4 A slightly modified mechanism for the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyls.

hydrolysis and β-H elimination of α-rhodium carbonyls could be tunable, even for the most enolizable α-rhodium ketones.

The competition of Heck-type coupling *vs.* conjugate addition observed in the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyls could be reasonably explained by the previously proposed mechanism with slight modifications (Scheme 4).

The β-H elimination of the α-rhodium carbonyl **2** required for Heck-type coupling to occur necessitates that the rhodium ion is unsaturatedly coordinated with respect to both steric and electronic aspects, which is closely related to the supporting ligand, phosphines. Thus, comparing with PPh_3, a chelating diphosphine, depressing the formation of an open coordinate site on rhodium ion of **2**, disfavors the Heck-type coupling, in other words, favoring the conjugate addition. The further increased CA selectivity with large bite angle diphosphines is obviously consistent with the shrinking of the coordination sphere available for approach of the β-H of alky moiety.[14] Structural effects of the carbonyls on the competition of hydrolysis *vs.* *β*-H elimination could be understood on the basis of carbonyl enolization and coordination. With carbonyls reluctant to enolize, for example, esters and amides, the Heck-type coupling could easily be promoted. For a substrate with readily enolizable carbonyl group, such as ketones, the Heck-type coupling is less favored than the conjugate addition. The beneficial effects of the presence of excess of a terminal olefin on Heck-type coupling come from the conversion of Rh–H species generated from β-H elimination into **3**, which is readily converted into Rh–Ar **1** through the OA–RE hydrolysis path followed by transmetallation, thus, favoring the Heck-type coupling. The co-existing OA–RE hydrolysis of the rhodium hydride with water, generating a rhodium hydroxide, Rh–OH, which is then converted into **1** through the transmetallation with aryl boronic acid, accounts for reasonable Heck-type coupling selectivity and yields in the reactions with one equivalent of α,β-unsaturated esters and amides. Higher HC selectivity under basic conditions, as opposed to neutral or acidic conditions, in the reactions of α,β-unsaturated esters and amides, is consistent with the OA–RE hydrolysis path for Rh–H instead of direct hydrolysis like ionic metal hydrides.

However, the increase of CA selectivity in the presence of excess aryl boronic acids is obscure in the currently accepted enolization–hydrolysis–transmetallation mechanism. For a given type of α,β-unsaturated carbonyl, the increase in CA selectivity upon increasing the concentration of aryl boronic acids means that the presence of excess aryl boronic acids in the reaction mixture would push the reaction to CA direction, implying that aryl boronic acids should be involved in the rate-determining steps in the cycle for conjugate addition. This would require a pre-condition for the enolization–hydrolysis–transmetallation mechanism of conjugate addition to work. That is, the transmetallation between aryl boronic acids and rhodium hydroxide, Rh–OH, has to be involved in the rate-determining steps in the conjugate addition, but not in the Heck-type coupling, since both cycles consist of the same step. Alternatively, we tentatively propose a direct transmetallation between the enolate **5** (instead of Rh–OH) and aryl boronic acids generating Rh–Ar species **1** and a boron enolate to explain the increase of the CA selectivity in the presence of excess aryl boronic acids, considering that boron enolates have been widely proposed in the reactions of carbonyl compounds promoted by dialkyl boronates.[16] Of course, increasing the proportion of aryl boronic acids means reduction of the proportion of olefins, which depressed the consumption of Rh–H *via* the conjugate reduction path, in other words, increased the conjugate addition selectivity.

Conclusions

In conclusion, through a systematic investigation of the factors affecting the selectivity of Heck-type coupling *vs.* conjugate addition, (discounting the intrinsic nature of rhodium and the enolization of carbonyls), we have found that the supporting ligands on rhodium, the ratio of aryl boronic acid to α,β-unsaturated carbonyl and the pH value of aqueous phase play important roles, even decisive in some cases, in the hydrolysis *vs.* *β*-H elimination competition of the α-rhodium carbonyl intermediates in the phosphine–rhodium catalyzed C–C bond forming reactions of aryl boronic acids with α,β-unsaturated carbonyls in the toluene–H_2O biphasic system. Subsequently, the reactions of aryl boronic acids with α,β-unsaturated esters, amides and ketones have been directed to favor both conjugate addition and Heck-type coupling by synergistically tuning the supporting ligands on rhodium, the boronic acid : olefin ratio and the other reaction conditions. In fact, the Heck-type coupling was carried out for acrylates, acrylamides and methyl vinyl ketone (MVK) with selectivity up to 100%, 98% and 84%, respectively, using PPh_3 as the supporting ligand with excess olefins in the presence of K_2CO_3, while higher than 99% conjugate addition selectivity was obtained using bidentate ligands with a large bite angle, such as dppp and binap, with excess boronic acids in the absence of K_2CO_3. These results clearly imply that high conjugate addition selectivity should not be assumed in the rhodium-catalyzed reactions of aryl boronic acids with α,β-unsaturated carbonyl compounds.

Acknowledgements

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References

1 For reviews: (*a*) K. Yoshida and T. Hayashi, in: *Modern Rhodium-Catalyzed Organic Reactions*, ed. P. A. Evans, Wiley-VCH, Weinheim, 2005, pp. 55-78; (*b*) K. Yoshida and T. Hayashi, in *Boronic Acids*, ed. D. G. Hall, Wiley-Vch Verlag GmbH & Co. KGaA, Weinheim, 2005, pp. 171-203; (*c*) T. Hayashi, *Pure Appl. Chem.*, 2004, **76**, 465–475; (*d*) T. Hayashi and K. Yamasaki, *Chem. Rev.*, 2003, **103**, 2829–2844; (*e*) K. Fagnou and M. Lautens, *Chem. Rev.*, 2003, **103**, 169–196; (*f*) T. Hayashi, *Synlett*, 2001, 879–887; For representative examples: (*g*) M. Sakai, H. Hayashi and N. Miyaura, *Organometallics*, 1997, **16**, 4229–4231; (*h*) Y. Takaya, M. Ogasawara, T. Hayashi, M. Sakai and N. Miyaura, *J. Am. Chem. Soc.*, 1998, **120**, 5579–5580; (*i*) M. Kuriyama, K. Nagai, K. Yamada, Y. Miwa, T. Taga and K. Tomioka, *J. Am. Chem. Soc.*, 2002, **124**, 8932–8939; (*j*) J.-F. Paquin, C. Defieber, C. R. J. Stephenson and E. M. Carreira, *J. Am. Chem. Soc.*, 2005, **127**, 10850–10851; (*k*) R. Shintani, W. Duan, T. Nagano, A. Okada and T. Hayashi, *Angew. Chem., Int. Ed.*, 2005, **44**, 4611–4614.

2 (*a*) T. Hayashi, M. Takahashi, Y. Takaya and M. Ogasawara, *J. Am. Chem. Soc.*, 2002, **124**, 5052–5058; (*b*) A. Kina, H. Iwamura and T. Hayashi, *J. Am. Chem. Soc.*, 2006, **128**, 3904–3905.

3 For Ru: (*a*) E. J. Farrington, J. M. Brown, C. F. J. Barnard and E. Rowsell, *Angew. Chem., Int. Ed.*, 2002, **41**, 169–171; For Ir: (*b*) T. Koike, X. Du, T. Sanada, Y. Danda and A. Mori, *Angew. Chem., Int. Ed.*, 2003, **42**, 89–92; For Pd: (*c*) C. S. Cho and S. Uemura, *J. Organomet. Chem.*, 1994, **465**, 85–92; (*d*) X. Du, M. Suguro, K. Hirabayashi, A. Mori, T. Nishikata, N. Hagiwara, K. Kawata, T. Okeda, H. F. Wang, K. Fugami and M. Kosugi, *Org. Lett.*, 2001, **3**, 3313–3316; (*e*) M. M. S. Andappan, P. Nilsson and M. Larhed, *Chem. Commun.*, 2004, 218–219.

4 A. Mori, Y. Danda, T. Fujii, K. Hirabayashi and K. Osakada, *J. Am. Chem. Soc.*, 2001, **123**, 10774–10775.

5 T. Yoshida, T. Okano, Y. Ueda and S. Otsuka, *J. Am. Chem. Soc.*, 1981, **103**, 3411–3422.

6 M. Lautens, A. Roy, K. Fukuoka, K. Fagnou and B. Martín-Matute, *J. Am. Chem. Soc.*, 2001, **123**, 5358–5359.

7 For examples of structurally characterized α-rhodium carbonyls: (*a*) C. Bianchini, C. Mealli, A. Meli, D. M. Proserpio, M. Peruzzini, F. Vizza and P. Frediani, *J. Organomet. Chem.*, 1989, **369**, C6–C10; (*b*) J. Ott, L. M. Venanzi, C. A. Ghilardi, S. Midollini and A. Orlandini, *J. Organomet. Chem.*, 1985, **291**, 89–100.

8 G. Zou, Z. Wang, J. Zhu and J. Tang, *Chem. Commun.*, 2003, 2438–2439.

9 (*a*) L. Navarre, S. Darses and J.-P. Genet, *Chem. Commun.*, 2004, 1108–1109; (*b*) L. Navarre, S. Darses and J.-P. Genet, *Adv. Synth. Catal.*, 2006, **348**, 317–322.

10 M. Lautens, J. Mancuso and H. Grover, *Synthesis*, 2004, 2006–2014.

11 J. L. Gras, K. J. Gombatz and G. Buchi, *Org. Synth.*, 1981, **60**, 88–90.

12 It was reported that $RhCl_3$ showed much better performance as a catalyst precursor than Rh(I) precursors, such as RhCl(cod), in the rhodium-catalyzed 1,2-addition of arylboronic acids to aldehydes: A. Fürstner and H. Krause, *Adv. Synth. Catal.*, 2001, **343**, 343–350.

13 For the bite angle data of phosphines see: (*a*) P. Dierkes and P. W. N. M. Leeuwen, *J. Chem. Soc., Dalton Trans.*, 1999, 1519–1529; (*b*) Z. Freixa and P. W. N. M. Leeuwen, *Dalton Trans.*, 2003, 1890–1901.

14 One of the reviewers suggests that the low activity of the smaller bidentates may be a consequence of forming coordinatively saturated tetraphosphine complexes of rhodium.

15 For cinnamaldehyde, instead of conjugate addition or Heck-type coupling, a new type of coupling-conjugate reduction cascade reaction occurred with the Rh–PPh_3 biphasic system. Z. Wang, G. Zou and J. Tang, *Chem. Commun.*, 2004, 1192–1193.

16 (*a*) A. Abiko, *Acc. Chem. Res.*, 2004, **37**, 387–395; (*b*) Y. Mori, K. Manabe and S. Kobayashi, *Angew. Chem., Int. Ed.*, 2001, **40**, 2815–2818; (*c*) Y. Mori, J. Kobayashi, K. Manabe and S. Kobayashi, *Tetrahedron*, 2002, **58**, 8263–8268; (*d*) K. Yoshida, M. Ogasawara and T. Hayashi, *J. Org. Chem.*, 2003, **68**, 1901–1905.