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$InCl_3$/Al mediated pinacol coupling reactions of aldehydes and ketones in aqueous media

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Abstract—A systematic work on the homo-pinacol coupling reactions of benzophenones, aldehydes, and acetophenones in aqueous media with $InCl_3$/Al is described for the first time, in which various 1,2-diols are obtained in moderate to good yields.

1. Introduction

From atom economy perspective, the reductive pinacol reaction of two carbonyl compounds is a powerful way to form the C–C bond of 1,2-diols.[1] Since the first report of the reaction of acetone with sodium in 1858,[2] various low-valent metals such as Al,[3] Sm,[4] V,[5] Mg,[6] Zn,[7] Mn,[8] Sn,[9] Ti,[10] Ce,[11] Te,[12] U,[13] Cr,[14] Ga,[15] and In[16] have been used to promote this reductive coupling reaction. Among these methods, some require absolutely anhydrous system under inert atmosphere, and some reagents and solvents are costly, moisture-sensitive, and toxic. In order to find environmental friendly condition, it is very attractive to develop a new convenient method for the pinacol coupling by utilizing less toxic reagents and solvents. During past decades, great efforts have been made by chemists to explore environmentally benign systems for pinacol reaction. Different catalysts/co-catalysts in aqueous media including $TiCl_3$, VCl_3/Al, Mn/HOAc, Al/MF, etc. have been reported with promising results.[17]

Water offers several advantages compared with organic solvents because of its low cost, safety, and operational simplicity. So recently organic reactions in water or aqueous media have attracted chemists' great interest.[18]

For a few decades, more attention has been paid to the development of new synthetic methods using indium chloride, which is nontoxic and compatible with water and air.[19] Recently, we have reported some $InCl_3$-mediated reactions,[20] which stimulates further exploration of the reactivity of $InCl_3$. $InCl_3$-catalyzed pinacol couplings of aromatic carbonyl compounds by using aluminum in the presence of chlorotrimethylsilane have been reported. But in this reaction anhydrous THF as solvent under nitrogen atmosphere was required.[16a,16c] Up to now, there is no report on the pinacol coupling reactions mediated by $InCl_3$/Al in aqueous media. We herein present a systematic study first on the pinacol coupling reactions of aromatic aldehydes and ketones by using $InCl_3$/Al in aqueous media.

2. Results and discussion

2.1. Optimization of $InCl_3$/co-reductant mediated pinacol coupling reaction of benzophenone

In our initial experiment, we examined the effect of the different metallic co-reductants and solvents on the pinacol coupling of benzophenone (Table 1). A mixture of benzophenone (1 mmol), indium chloride (1 mmol), NH_4Cl (1 g), commercial aluminum powder (3.5 mmol), and 50% aqueous EtOH (4 mL) was stirred at 80 °C for 5 h. Compound **2a** was obtained as the only product in high yield (Table 1, entry 1). The absence of NH_4Cl decreased the yield greatly (Table 1, entry 2). No desired product was obtained without indium chloride (Table 1, entry 3). When 1 mmol of indium chloride was combined with 3.5 mmol of co-reductant Zn or Fe, no reaction occurred (Table 1, entries 4 and 5). But similar treatment with co-reductant Mg afforded the pinacol **2a** in 22% yield (Table 1, entry 6). These results showed that metallic Al was more efficient as a co-reductant than others. Several solvents, such as EtOH, H_2O, 50% aqueous EtOH (pH=1–2), 50% aqueous EtOH (pH=11–12), and THF,

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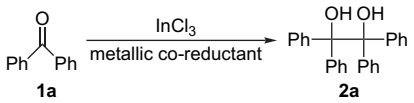
Table 1. Effect of indium chloride, metallic co-reductant, and solvent on the pinacol coupling of benzophenone[a]



1a 2a

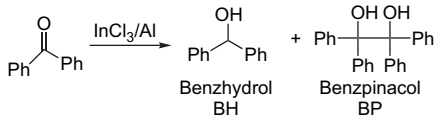
Entry	Reductant	Solvent (mL)	NH_4Cl (g)	Time (h)	Yield[c] (%)
1	$InCl_3$/Al	EtOH (2), H_2O (2)	1	5	92
2	$InCl_3$/Al	EtOH (2), H_2O (2)	—	5	62
3	Al	EtOH (2), H_2O (2)	1	11	0
4	$InCl_3$/Zn	EtOH (2), H_2O (2)	1	11	0
5	$InCl_3$/Fe	EtOH (2), H_2O (2)	1	11	0
6	$InCl_3$/Mg	EtOH (2), H_2O (2)	1	11	22
7	$InCl_3$/Al	EtOH (4)	1	11	0
8	$InCl_3$/Al	H_2O (4)	1	11	15
9	$InCl_3$/Al	EtOH (2), H_2O (2), pH=1–2[b]	—	11	67
10	$InCl_3$/Al	EtOH (2), H_2O (2), pH=11–12[b]	—	11	13
11	$InCl_3$/Al	THF (4)	1	11	Trace
12[d]	$InCl_3$(Cat.)/Al	EtOH (2), H_2O (2)	1	11	30

[a] Reaction conditions: benzophenone (1 mmol), indium chloride (1 mmol), co-reductant Al, Zn, Fe or Mg (3.5 mmol), 80 °C.
[b] pH was adjusted by concentrated hydrochloric acid or solid sodium hydroxide.
[c] Isolated yield.
[d] $InCl_3$ (20 mol %) was used.

were also surveyed by using $InCl_3$/Al as the reducing agent. Most of the reactions worked poorly except that 50% aqueous EtOH (pH=1–2) gave a moderate yield (Table 1, entries 7–11). When catalytic $InCl_3$ was used, only 30% yield was obtained (Table 1, entry 12).

In the following experiment, different temperatures were also surveyed by using benzophenone as an example [benzophenone (1 mmol), indium chloride (1 mmol), co-reductant Al (3.5 mmol), and 50% aqueous EtOH (4 mL)] (Table 2). Only compound **2a** was obtained at 80 or 90 °C (Table 2, entries 1 and 2). However, the lower temperatures (50–70 °C) yielded two products, the corresponding alcohol—benzhydrol (BH) and the coupling product—benzpinacol (BP) (Table 2, entries 3–5). It was interesting that when the reaction temperature dropped, the ratio of BH/BP increased

Table 2. Effect of the temperature on benzhydrol (BH):benzpinacol (BP) ratios in the reduction of benzophenone **1a**[a,b]



Entry	T (°C)	Time (h)	BH[b]	BP[b]	Total yield (BH+BP)[c] (%)
1	90	5	—	100	93
2	80	5	—	100	92
3	70	5	24	76	94
4	60	6	50	50	90
5	50	11	64	36	55
6	rt	26	100	—	Trace

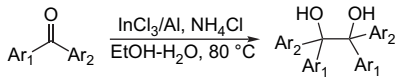
[a] Reaction conditions: benzophenone **1a** (1 mmol), indium chloride (1 mmol), Al powder (3.5 mmol).
[b] The ratios were determined by isolated yields and did not represent yields.
[c] Total isolated yield (BH+BP).

accordingly. The reaction at the room temperature gave the trace benzhydrol as the only product (Table 2, entry 6). These results proved that the higher temperature is in favor of the pinacol coupling of benzophenone by using $InCl_3$/Al reagent. With the emphasis on the search for the pinacol coupling of aldehydes and ketones to form carbon–carbon bond, 80 °C was chosen as the optimized temperature.

2.2. $InCl_3$/Al mediated pinacol coupling of substituted benzophenones in 50% aqueous alcohol

Under the optimized conditions (Table 1, entry 1), various substituted benzophenones were investigated to give a series of 1,1′,2,2′-tetraaryl substituted 1,2-diols (**2a–g**) (Table 3). From these results, we found that **2a–c** were obtained in excellent yields without formation of by-product due to reduction of the carbonyls to the corresponding alcohols (Table 3, entries **a–c**). Benzophenones bearing electron-donating groups (**1d**,**e**) *para* to ketones were reduced to the corresponding pinacols in the moderate yields even after 11 h (Table 3, entries **d** and **e**). Unfortunately, the reactions of benzophenones bearing electron-withdrawing groups (**1f**,**g**) *para* to ketones with $InCl_3$/Al reagent at 80 °C for 3 h gave miscellaneous products, in which most starting materials had been consumed (Table 3, entries **f** and **g**). On the other hand, lower temperature gave pinacols in moderate yields (Table 3, entries $\mathbf{f}^0$ and $\mathbf{g}^0$) along with a small quantity of the corresponding alcohols. Unexpectedly, benzophenone bearing a chlorine group (**1h**) *ortho* to ketone only gave the corresponding alcohol as the main product.

Table 3. Pinacol coupling of substituted benzophenones by using $InCl_3$/Al reagent[a]



1a-h 2a-g

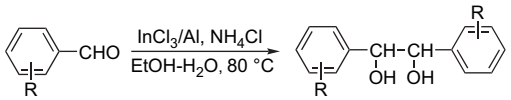
Entry	Ar_1	Ar_2	Time (h)	Yield of **2**[c] (%)
a	C_6H_5	C_6H_5	5	**2a**, 92
b	4-$CH_3C_6H_4$	C_6H_5	5	**2b**, 90
c	4-FC_6H_4	4-FC_6H_4	5	**2c**, 98
d	4-$(OCH_3)C_6H_4$	4-FC_6H_4	11	**2d**, 48
e	4-$(OCH_3)C_6H_4$	C_6H_5	11	**2e**, 72
f	4-ClC_6H_4	C_6H_5	3	Mixture
g	4-$(C_6H_5)C_6H_4$	C_6H_5	3	Mixture
$\mathbf{f}^0$	4-ClC_6H_4	C_6H_5	5[b]	**2f**, 64
$\mathbf{g}^0$	4-$(C_6H_5)C_6H_4$	C_6H_5	5[b]	**2g**, 65
h	2-ClC_6H_4	C_6H_5	5	—, (52)[d]

[a] Reaction conditions: **1** (1 mmol), indium chloride (1 mmol), Al powder (3.5 mmol); 80 °C except pointed out especially.
[b] 60 °C.
[c] Isolated yield.
[d] Only the corresponding alcohol was obtained.

2.3. $InCl_3$/Al mediated pinacol coupling of substituted benzaldehydes in 50% aqueous alcohol

When a mixture of benzaldehyde, Al powder, $InCl_3$, and NH_4Cl in 50% aqueous EtOH was stirred for 2 h at 80 °C, **4a** was obtained in 88% yield (*meso*/*dl*=40/60). Similar treatment of substituted benzaldehydes **3b–h** gave **4b–g** as shown in Table 4. In all cases except for **3g** and **3h**, **4** was obtained in satisfactory yield with poor *meso*/*dl* ratios.

Table 4. Pinacol coupling of benzaldehydes **3** by using $InCl_3$/Al reagent[a]



3a-h **4a-g**

Entry	R	Time (h)	*meso*/*dl*[b]	Yield of **4**[c] (%)
a	H	2	40/60	**4a**, 88
b	2-Cl	2	66/34	**4b**,78
c	4-Cl	2	30/70	**4c**, 80
d	2-F	2	62/38	**4d**, 84
e	2-Br	2	71/29	**4e**, 80
f	4-CH_3	11	56/44	**4f**, 78
g	4-OCH_3	11	—	**4g**, trace
h	2-OCH_3	11	—	—, (18)[d]

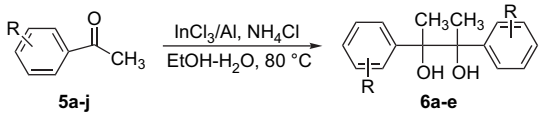
[a] Reaction conditions: **3** (1 mmol), indium chloride (1 mmol), Al powder (3.5 mmol), NH_4Cl (1 g), 80 °C.
[b] Determined by ^1H NMR.
[c] Isolated yield.
[d] Only the corresponding alcohol was obtained.

Benzaldehydes bearing electron-donating groups (**3g**,**h**) were reduced slowly compared with **3a**–**e**. The coupling reaction of **3g** at 80 °C for 11 h in 50% aqueous EtOH only gave a trace yield. However, the corresponding alcohol as the main product was obtained in the reduction of **3h** (Table 4, entry **h**). It was supposed that steric hindrance plays a great role in the pinacol coupling. Large group *ortho* to aldehyde cumbers coupling of the intermediate.

2.4. $InCl_3$/Al mediated pinacol coupling of substituted acetophenones in 50% aqueous alcohol

The $InCl_3$/Al reagent was also effective for the coupling of substituted acetophenones **5a**–**e** (Table 5, entries **a**–**e**). As compared with **1** and **3**, pinacol reaction of **5** was slightly sluggish. When the coupling reactions of **5a**–**e** with $InCl_3$/Al reagent were carried out at 80 °C for 11 h, **6a**–**e** were obtained in less than 64% yield. Acetophenone **5f** bearing *para* nitro-group was reduced to **5g**. Considering possible insufficiency of the reducing agent, the coupling of **5g** was investigated and most starting material was obtained (Table 5, entry **g**). Similarly, the reaction of **5h** gave **5i**. For **5i** and **5j**, no reaction occurred. From these results, we found that the compounds containing nitro group and esters were incompatible with the $InCl_3$/Al reagent, which could be reduced or hydrolyzed, respectively.

Table 5. Pinacol coupling of acetophenones **5** by using $InCl_3$/Al reagent[a]



5a-j **6a-e**

Entry	R	*meso*/*dl*[b]	Yield of **6**[c] (%)
a	H	49/51	**6a**, 52
b	4-CH_3	46/54	**6b**, 33
c	2-CH_3	52/48	**6c**, 31
d	4-Cl	45/55	**6d**, 64
e	2-Br	45/55	**6e**, 48
f	4-NO_2	—	**5g**, 98
g	4-NH_2	—	—
h	4-CH_3COO	—	**5i**, 98
i	4-OH	—	—
j	3-OCH_3	—	—

[a] Reaction conditions: **5** (1 mmol), indium chloride (1 mmol), Al powder (3.5 mmol), NH_4Cl (1 g), 80 °C, 11 h.
[b] Determined by ^1H NMR.
[c] Isolated yield.

In order to investigate the limitation of the scope of the substrates for this reaction condition, the pinacol coupling of aliphatic ketone was investigated, for example, cycloheptanone. After carrying out the reaction of cycloheptanone by using $InCl_3$/Al reagent in 50% aqueous EtOH at 80 °C for 11 h, no reduced product was monitored.

The mechanism of metal reduction of the carbonyl compound is generally believed to proceed through the coupling of a ketyl radical anion formed by electron transfer from the metal to the carbonyl substrate.[1] In our experiment, the similar mechanism is possible. Activated indium generated in situ by $InCl_3$/Al reduces the carbonyl to the radical anion to form the pinacol product. Although the reaction in absolute water only gives unsatisfactory yield (Table 1, entry 8), in this reaction system water seems to be critical. This gains support from the fact that no reduced product was obtained in the reactions of benzophenone in absolute ethanol even after stirred for 11 h (Table 1, entry 7). It is possible that the coupling of ketyl radical anions seems to take place in an aqueous medium at a much faster rate compared to further electron transfer from the metal surface resulting in preferential formation of the diol over the reduced alcohol.[21] Moreover, it was proved that high temperature is in favor of the coupling of ketyl radical anions. According to all the experimental results, it was thought that carbonyl compounds bearing electron-withdrawing group have higher reactivity than those of bearing electron-donating groups in the pinacol coupling generally. Steric hindrance *ortho* to carbonyl group could affect the coupling of ketyl radical anions in which the effect is the most in pinacol couplings of benzophenones and the least in those of benzaldehydes. As compared with commercial metal indium, indium generated in situ can avoid the refractory metal oxide surface problem in aqueous media.

3. Conclusion

We have demonstrated that $InCl_3$/Al reagent can be used for the pinacol reactions of benzophenones, benzaldehydes, and acetophenones in aqueous media successfully. The effect of the different groups on the yield and the stereoselectivity has been also investigated systematically by using the optimized reaction condition. The important advantage of the present method includes (a) operational simplicity, (b) less toxic reagents and solvent. Therefore, it is considered to be an environmental friendly synthetic method. Further investigation of the mechanism of this reaction is currently underway.

4. Experimental

4.1. General

The ^1H NMR and ^{13}C NMR spectra were obtained with a Bruker AVANCE DRX-500 NMR spectrometer (^1H,

500 MHz; ^{13}C, 125 MHz) with TMS as internal standard and $CDCl_3$ as solvent. The ESI-MS spectra were taken on a Bruker Esquire 3000 plus spectrometer. Precoated thin-layer plates of silica gel 60 GF_{254} (Qingdao Haiyang Chemical Co. Ltd, Qingdao, China) were used for analytical purposes. All the benzophenones, benzaldehydes, and acetophenones were purchased from J&K chemical Co., or other commercial suppliers and were used after appropriate purification (distillation).

4.2. General procedure for the pinacol coupling reactions of substituted benzophenones in 50% aqueous alcohol

A suspension of benzophenones **1** (1 mmol), indium chloride (1 mmol), Al powder (3.5 mmol), and NH_4Cl (1 g) in 50% aqueous EtOH was stirred vigorously at 80 °C until the reaction was completed (monitored by TLC). The reaction was quenched with 1 N HCl (3 mL) and extracted with ether (3×20 mL). The combined organic layers were washed with brine, dried over sodium sulfate, and filtered. The filtrate was concentrated under reduced pressure. Purification by silica gel column chromatography (200–300 mesh) with petroleum ether (60–90 °C) and ethyl acetate as eluent afforded the corresponding products (**2a–g**, the product of **1h**).

4.2.1. 1,1,2,2-Tetraphenyl-ethane-1,2-diol (2a). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 3.03 (s, 2H, OH), 7.15–7.20 (m, 12H, Ph), 7.28–7.30 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 83.13, 127.10, 127.44, 128.72, 144.25; ESI-MS *m/z*: 389.0 $[M+Na]^+$.

4.2.2. 1,2-Diphenyl-1,2-di-*p*-tolyl-ethane-1,2-diol (2b). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.25 (*dl*, s, 6H, Me), 2.26 (*meso*, s, 6H, Me), 2.99 (s, 2H, OH), 6.94–6.97 (m, 4H, Ph), 7.11–7.15 (m, 10H, Ph), 7.29–7.33 (m, 4H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 21.18, 83.10, 126.91, 126.98, 127.39, 127.41, 128.21, 128.24, 128.66, 128.71, 128.76, 128.81, 136.65, 136.74, 141.37, 141.42, 144.61, 144.64; ESI-MS *m/z*: 416.9 $[M+Na]^+$.

4.2.3. 1,1,2,2-Tetrakis-(4-fluorophenyl)-ethane-1,2-diol (2c). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 6.85–6.89 (m, 8H, Ph), 7.23–7.25 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 82.72, 114.37, 114.54, 130.39, 130.46, 139.80, 160.97, 162.93; ESI-MS *m/z*: 460.9 $[M+Na]^+$.

4.2.4. 1,2-Di(4-fluorophenyl)-1,2-di(4-methoxyphenyl)-ethane-1,2-diol (2d). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.96 (s, 2H, OH), 3.71 (*dl*, s, 6H, OMe), 3.72 (*meso*, s, 6H, OMe), 6.67–7.41 (m, 16H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 55.18, 55.22, 82.72, 112.80, 113.95, 113.97, 114.11, 114.14, 129.78, 129.82, 130.43, 130.50, 130.57, 135.90, 136.16, 140.47, 158.50, 158.67, 160.57, 160.71, 162.52, 162.66; ESI-MS *m/z*: 484.9 $[M+Na]^+$.

4.2.5. 1,2-Diphenyl-1,2-di(4-methoxyphenyl)-ethane-1,2-diol (2e). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.96 (s, 2H, OH), 3.74 (s, 6H, OMe), 6.68–7.30 (m, 18H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 55.24, 82.97, 112.67, 126.96, 127.38, 128.72, 129.96, 136.45, 144.61, 158.39; ESI-MS *m/z*: 449.0 $[M+Na]^+$.

4.2.6. 1,2-Diphenyl-1,2-di(4-chlorophenyl)-ethane-1,2-diol (2f). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.96 (s, 2H, OH), 7.08–7.41 (m, 18H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 82.90, 127.51, 127.55, 127.65, 127.70, 127.76, 128.41, 128.48, 130.24, 130.27, 132.98, 133.16, 142.86, 143.36, 143.66; ESI-MS *m/z*: 456.7 $[M+Na]^+$.

4.2.7. 1,2-Diphenyl-1,2-di(4-phenylphenyl)-ethane-1,2-diol (2g). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 3.09 (s, 2H, OH), 7.19–7.57 (m, 28H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 83.22, 126.07, 127.11, 127.21, 127.44, 127.52, 128.71, 128.78, 128.87, 129.21, 129.28, 139.65, 140.59, 143.40, 143.40, 144.24; ESI-MS *m/z*: 540.8 $[M+Na]^+$.

4.2.8. The product of 1h: (2-chlorophenyl)-phenyl-methanol. White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.45 (s, 1H, OH), 6.18 (s, 1H, CH), 7.20–7.59 (m, 9H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 83.13, 127.10, 127.44, 128.72, 144.25; ESI-MS *m/z*: 240.7 $[M+Na]^+$.

4.3. General procedure for the pinacol coupling reactions of substituted benzaldehydes in 50% aqueous alcohol

General procedure for the pinacol coupling reactions of substituted benzaldehydes is similar to that of benzophenones. The corresponding products (**4a–f**, the product of **3h**) were obtained.

4.3.1. 1,2-Diphenyl-ethane-1,2-diol (*meso*/*dl* mixture) (4a). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.85 (br, 2H, OH), 4.67 (*dl*, s, 2H, CH), 4.80 (*meso*, s, 2H, CH), 7.09–7.31 (m, 10H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 78.12, 79.21, 127.08, 127.22, 128.03, 128.19, 128.24, 128.32, 139.87, 139.98; ESI-MS *m/z*: 236.6 $[M+Na]^+$.

4.3.2. 1,2-Di(2-chlorophenyl)-ethane-1,2-diol (*meso*/*dl* mixture) (4b). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.97 (s, 2H, OH), 5.31 (*dl*, s, 2H, CH), 5.56 (*meso*, s, 2H, CH), 7.11–7.61 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 72.17, 73.14, 76.93, 77.18, 77.44, 126.55, 126.95, 128.91, 128.97, 129.27, 129.56, 132.74, 133.48, 136.50, 137.37; ESI-MS *m/z*: 304.6 $[M+Na]^+$.

4.3.3. 1,2-Di(4-chlorophenyl)-ethane-1,2-diol (*meso*/*dl* mixture) (4c). White solid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.94 (br, 2H, OH), 4.60 (*dl*, s, 2H, CH), 5.81 (*meso*, s, 2H, CH), 7.00–7.26 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 76.89, 78.65, 128.45, 128.48, 128.52, 133.99, 138.05; ESI-MS *m/z*: 280.8 $[M-H]^-$.

4.3.4. 1,2-Di(2-fluorophenyl)-ethane-1,2-diol (*meso*/*dl* mixture) (4d). Viscous liquid; ^1H NMR ($CDCl_3$, 500 MHz) δ 3.09 (s, 2H, OH), 5.13 (*dl*, s, 2H, CH), 5.35 (*meso*, s, 2H, CH), 6.88–7.43 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 70.72, 72.12, 114.93, 115.11, 115.31, 115.48, 124.04, 124.07, 124.32, 126.53, 126.63, 128.47, 128.50, 128.65, 129.49, 129.56, 129.74, 129.81, 159.32, 161.27; ESI-MS *m/z*: 272.6 $[M+Na]^+$.

4.3.5. 1,2-Di(2-bromophenyl)-ethane-1,2-diol (*meso*/*dl* mixture) (4e). Viscous liquid; ^1H NMR ($CDCl_3$, 500 MHz) δ 2.79 (s, 2H, OH), 5.30 (*dl*, s, 2H, CH), 5.54 (*meso*, s, 2H,

CH), 7.07–7.68 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 74.49, 75.34, 123.08, 124.13, 127.19, 127.61, 129.36, 129.38, 129.69, 129.86, 132.26, 132.92, 138.00, 138.88; ESI-MS *m/z*: 392.6 $[M+Na]^+$.

4.3.6. 1,2-Di(4-methylphenyl)-ethane-1,2-diol (*meso*/*dl* mixture) (4f). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 2.28 (*dl*, s, 6H, Me), 2.32 (*meso*, s, 6H, Me), 2.67 (br, 2H, OH), 4.60 (*dl*, s, 2H, CH), 4.70 (*meso*, s, 2H, CH), 6.97–7.14 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 21.28, 21.31, 78.13, 78.90, 127.01, 127.19, 128.92, 129.08, 137.12, 137.16, 137.55, 137.86; ESI-MS *m/z*: 264.6 $[M+Na]^+$.

4.3.7. The product of 3h: (2-methoxyphenyl)methanol. White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 2.32 (s, 1H, OH), 3.86 (s, 3H, Me), 4.68 (s, 2H, CH), 6.89–7.28 (m, 4H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 55.38, 62.26, 110.33, 120.78, 128.88, 129.09, 129.18, 157.58; ESI-MS *m/z*: 160.7 $[M+Na]^+$.

4.4. General procedure for the pinacol coupling reactions of substituted acetophenones in 50% aqueous alcohol

General procedure for the pinacol coupling reactions of substituted acetophenones is similar to that of benzophenones. The corresponding products (**6a–e**, **5g**, and **5i**) were obtained.

4.4.1. 2,3-Diphenyl-butane-2,3-diol (*meso*/*dl* mixture) (6a). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.48 (*dl*, s, 6H, Me), 1.57 (*meso*, s, 6H, Me), 7.17–7.24 (m, 10H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 25.15, 25.31, 78.84, 79.09, 127.12, 127.17, 127.28, 127.38, 127.50, 127.62, 143.65, 144.01; ESI-MS *m/z*: 264.8 $[M+Na]^+$.

4.4.2. 2,3-Di(4-methylphenyl)-butane-2,3-diol (*meso*/*dl* mixture) (6b). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.45 (*dl*, s, 6H, Me), 1.53 (*meso*, s, 6H, Me), 2.33 (s, 6H, PhMe), 7.03–7.15 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 21.21, 21.24, 25.27, 25.45, 78.76, 79.01, 127.10, 127.54, 128.09, 128.25, 136.24, 136.79, 140.77, 141.12; ESI-MS *m/z*: 292.7 $[M+Na]^+$.

4.4.3. 2,3-Di(2-methylphenyl)-butane-2,3-diol (*meso*/*dl* mixture) (6c). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.71 (*dl*, s, 6H, Me), 1.72 (*meso*, s, 6H, Me), 2.07 (s, 6H, PhMe), 6.96–7.25 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 23.26, 23.49, 27.46, 82.47, 82.84, 124.95, 124.99, 127.28, 127.42, 129.53, 130.06, 132.85, 132.91, 137.52, 137.97, 141.54, 141.60; ESI-MS *m/z*: 292.7 $[M+Na]^+$.

4.4.4. 2,3-Di(4-chlorophenyl)-butane-2,3-diol (*meso*/*dl* mixture) (6d). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.43 (*dl*, s, 6H, Me), 1.52 (*meso*, s, 6H, Me), 7.04–7.08 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 24.94, 25.25, 78.49, 78.75, 127.54, 127.60, 128.72, 129.07, 133.21, 133.40, 141.95, 142.41; ESI-MS *m/z*: 332.7 $[M+Na]^+$.

4.4.5. 2,3-Di(2-bromophenyl)-butane-2,3-diol (*meso*/*dl* mixture) (6e). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 1.51 (*dl*, s, 6H, Me), 1.60 (*meso*, s, 6H, Me), 7.20–7.27 (m, 8H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 25.06, 25.23, 78.74, 79.00, 127.03, 127.08, 127.18, 127.28, 127.41, 127.52, 143.57, 143.93; ESI-MS *m/z*: 420.7 $[M+Na]^+$.

4.4.6. 1-(4-Amino-phenyl)-ethanone (5g). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 2.49 (s, 3H, Me), 4.35 (s, 2H, NH_2), 6.62–6.64 (m, 2H, Ph), 7.78–7.80 (m, 2H, Ph); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 26.23, 113.81, 127.63, 130.96, 151.68, 196.84; ESI-MS *m/z*: 135.7 $[M+H]^+$.

4.4.7. 1-(4-Hydroxy-phenyl)-ethanone (5i). White solid; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 2.61 (s, 3H, Me), 7.12–7.57 (m, 5H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 26.54, 115.89, 129.49, 131.59, 162.04, 199.46; ESI-MS *m/z*: 136.7 $[M+H]^+$.

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2006.10.061.

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