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Synthesis of 2,3-dihydro-1*H*-inden-1-one derivatives via Ni-catalyzed intramolecular hydroacylation

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ABSTRACT

An efficient synthetic method for the formation of 2,3-dihydro-1*H*-inden-1-one derivatives through a Ni-catalyzed intramolecular hydroacylation of 2-(prop-2-ynyl)benzaldehydes has been developed. Examination of various nickel and other transition metal catalysts and phosphine ligands showed that the use of $Ni(COD)_2$ catalyst combined with $P(i\text{-}Pr)_3$ ligand was the best choice to the success of the present intramolecular hydroacylation. A wide range of functional groups were tolerated, affording the corresponding substituted α-lidene-2,3-dihydro-1*H*-inden-1-ones in good to high yields with a sole *E*-selectivity under present reaction conditions.

1. Introduction

Transition metal-catalyzed hydroacylation of alkenes and alkynes is one of attractive atom-economical methodologies for the formation of new C–C bonds in organic synthesis through functionalization of C–H bonds.[1] However, hydroacylation for the alkene-based process has been well developed, the catalytic hydroacylation of alkynes has received less attention. Recent advances on both inter- and intramolecular hydroacylation of alkynes proved that the use of rhodium catalysts is one of the best choices to realize these transformations. For examples, Fu and Tanaka groups reported the intramolecular hydroacylation of the alkyl-tethered 4-, 5-, and 6-alkynals using different kinds of cationic rhodium complexes,[2] and Bendorf group developed the S-chelation-assisted Rh-catalyzed intramolecular alkyne hydroacylations to give the seven- and eight-membered α-alkylidenes in good yields,[3] Jun has selectively synthesized the branched α,β-enones by applying Rh/picoline catalyst system to intermolecular hydroacylation of alkynes,[4] and some interesting Rh-catalyzed *O*- and *S*-chelating systems have also been applied to the intermolecular alkyne hydroacylation reactions.[5] Other transition metal catalysts were also applied to the alkyne hydroacylations. For examples, Krische group demonstrated that alkyne hydroacylation could be applied to the ruthenium catalyzed transfer hydrogenation-based method,[6] and Tusda reported an intermolecular hydroacylation of aldehydes and alkynes by using Ni comlpexes as catalyst forming the corresponding enones with *E*-isomers as major products.[7] These results indicated that the choice of catalyst and ligand, and the use of appropriate structure of the starting substrate should be crucial to the success of these reactions.

In the continuation of our interests in the study of reactivity of 2-(prop-2-ynyl)benzaldehyde derivatives,[8] herein, we report an efficient Ni-catalyzed intramolecular hydroacylation of 2-(prop-2-ynyl)benzaldehyde derivatives **1** affording a variety of substituted α-lidene-2,3-dihydro-inden-1-ones **2** in good to high yields [Eq. 1]. α-Lidene-2,3-dihydro-1*H*-inden-1-one is important framework found in pharmaceutically active compounds and used as valuable intermediates in organic synthesis.[9] To date, Aldol condensation of 1*H*-inden-1-ones with aldehydes is still the most common approach for synthesis of α-lidene-2,3-dihydro-inden-1-ones.[10] Recently, new synthetic method of this framework has been reported, for example, a Pd-catalyzed carbonylation of arynes with allyl acetates or carbonates.[11] Our methodology for synthesizing indenones with a wide range of functional groups provides a new entry for this important framework.

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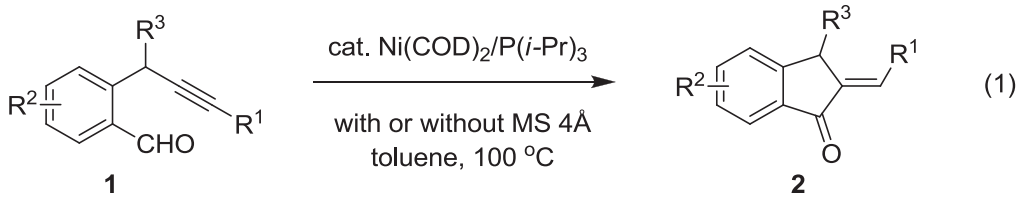
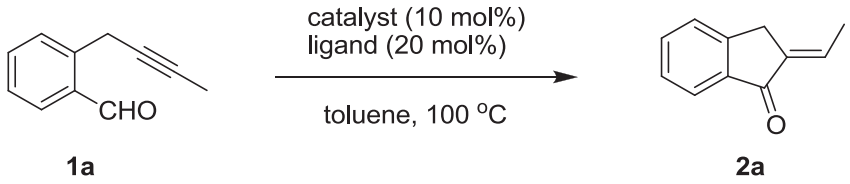


2. Results and discussion

In the preliminary studies, we investigated metal catalysts and phosphine ligands on the intramolecular hydroacylation of 2-(but-2-ynyl)benzaldehyde **1a** for the formation of the (*E*)-2-ethylidene-2,3-dihydro-1*H*-inden-1-one **2a** in toluene at 100 °C under Ar atmosphere (Table 1). The use of $Ni(COD)_2$ catalyst without phosphine ligand, the reaction did not proceed at all (entry 1). The use of triarylphosphine ligand, PPh_3 showed a lower reactivity, producing **2a** in 14% yield (entry 2). Among the trialkylphosphine ligands tested, the sterically less hindered or bulky phosphine ligands, such as PMe_3 (28%), P(*n*-Pr)$_3$ (70%), P(*t*-Bu)$_3$ (35%), and PCy_3 (8%), exhibited lower reactivity compared to that of P(*i*-Pr)$_3$ (86% isolated yield), indicating that phosphine ligand both having a strong electron donating property and adequate bulkiness was the best choice in the present hydroacylation (entries 3–5, 8, and 9). It should be noted that the decrease or increase of the amount of P(*i*-Pr)$_3$ ligand resulted in lower yields of **2a** (entries 6 and 7). The use of bidentate phosphine ligand, dppe did not show obvious influence on the catalytic activity (entry 10). Other catalysts, such as $Ni(CO)_2(PPh_3)_2$, $[Ir(COD)Cl]_2$, $RuHCl(CO)PPh_3$ combined with P(*i*-Pr)$_3$ ligand gave lower yields of **2a** (entries 11–13). It was noted that the use of cationic rodium catalyst [Rh(binap)]BF_4, which was employed by Tanaka group[2b] gave **2a** in 40% yield (entry 14). It was noteworthy that the corresponding product **2a** was obtained as a sole *E*-selectivity, which was determined by the reported authentic compound.[10a]

reactions of substrates bearing an alkyl groups, such as ethyl (**1b**) and *n*-hexyl (**1c**) at the alkynyl terminus (R^1) produced the corresponding 1*H*-inden-1-ones **2b** and **2c** in 83% and 78% yield, respectively (entries 1 and 2, condition A). In contrast, the reaction of substrate **1d** having a phenyl substituent at R^1 dramatically decreased the yield of **2a** under same conditions even though the higher loadings of Ni and phosphine catalysts were used (entries 3 and 4). We thought that the lower yield might be due to the decomposition of **2d** in the presence of a trace amount of water. Thus, the reaction was carried out in the presence of molecular sieves 4 Å under a higher catalyst loading, affording **2a** in 78% yield (entry 5, condition B). Under this reaction condition B, various aryl groups at R^1 were tested. The reactions of substrates bearing an electron-withdrawing (**1e**) and an electron-donating (**1f** and **1g**) aromatic group at R^1 produced the corresponding products **1e**–**g** in 75–63% yields (entries 6–8). Substrates **1h** and **1i** having a naphthyl and conjugated cyclohexenyl group afforded the desired products in moderate yields (entries 9 and 10). Substrates **1j** and **1k** having heteroaromatic rings at R^1, such as furanyl and thienyl, showed a high compatibility with the present reaction conditions, producing **2j** and **2k** in high yields (entries 11 and 12). The electronic characteristics of the benzaldehyde moiety of **1** exert obvious influence on the yields of products **2**. For examples, substrates **1l** and **1m** having an electron-withdrawing group (−F, or −Cl) at R^2 decreased the yields of **2l** and **2m**, while the reaction worked well with the substrates **1n** and **1o**, substituted with an electron-donating group (dimethoxy, −Me) at R^2, furnishing the expected

Table 1
Optimization of reaction conditions for the intramolecular hydroacylation of 2-(but-2-ynyl)benzaldehyde **1a**[a]



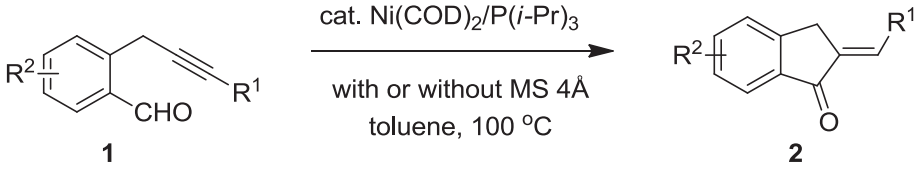
1a **2a**

Entry	Catalyst (10 mol %)	P ligand (20 mol %)	**2a**[b] (%)
1	$Ni(COD)_2$	None	0
2	$Ni(COD)_2$	PPh_3	14
3	$Ni(COD)_2$	PMe_3	28
4	$Ni(COD)_2$	P(*n*-Pr)$_3$	70
5	$Ni(COD)_2$	P(*i*-Pr)$_3$	92 (86)
6	$Ni(COD)_2$	P(*i*-Pr)$_3$ (10 mol %)	61
7	$Ni(COD)_2$	P(*i*-Pr)$_3$ (40 mol %)	64
8	$Ni(COD)_2$	P(*t*-Bu)$_3$	35
9	$Ni(COD)_2$	PCy_3	8
10	$Ni(COD)_2$	dppe	34
11	$Ni(CO)_2(PPh_3)_2$	P(*i*-Pr)$_3$	74
12[c]	$[Ir(COD)Cl]_2$	P(*i*-Pr)$_3$	7
13	$RuHCl(CO)PPh_3$	P(*i*-Pr)$_3$	19
14	[Rh(binap)]BF_4	None	40

[a] Reaction conditions: **1a** (0.2 mmol), anhydrous toluene (0.1 M), 100 °C, 18 h under Ar atmosphere.
[b] ^1H NMR yield determined using CH_2Br_2 as an internal standard. Isolated yield is shown in parentheses.
[c] Catalyst (5 mol %) was used.

The scope and limitations of $Ni(COD)_2$/P(*i*-Pr)$_3$-catalyzed intramolecular hydroacylation of various 2-(prop-2-ynyl)benzaldehydes **1** in toluene under Ar atmosphere were summarized in Table 2. The products **2n** and **2o** in high yields (entries 13–16). When substrate **1p** having a methoxy group at R^3 was used, the reaction proceeded smoothly, furnishing the multisubstituted inden-1-one product **2p**

Table 2
Ni-catalyzed hydroacylation of various 2-(prop-2-ynyl)benzaldehydes[a]

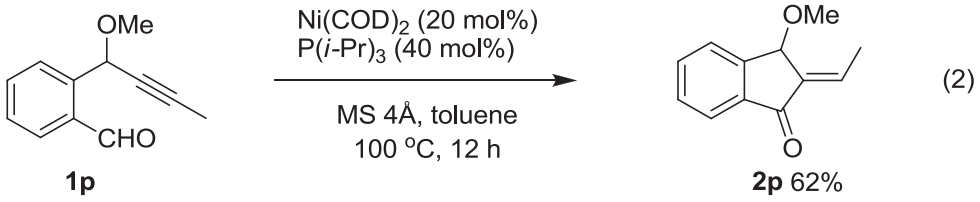


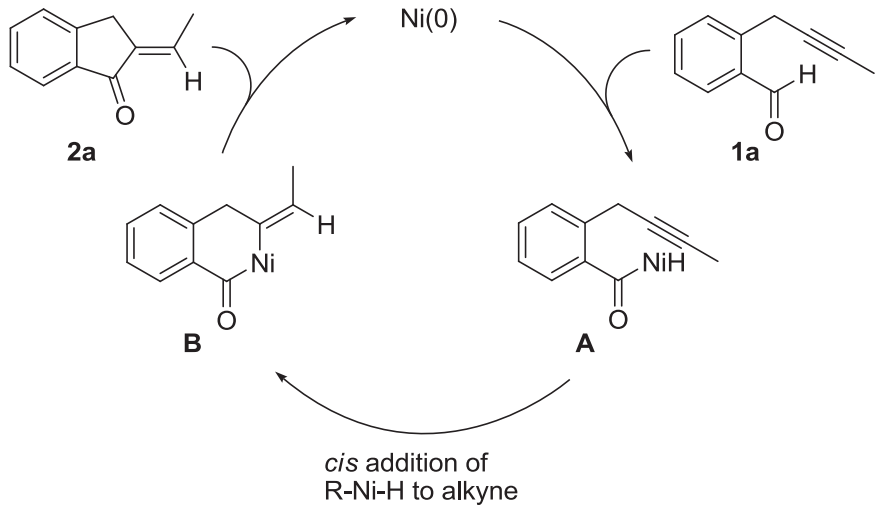
Entry	Substrate	1	Conditions	2	Yield[b] (%)
1	R^1=Et, R^2=H	**1b**	**A**	**2b**	83
2	R^1=*n*-Hexyl, R^2=H	**1c**	**A**	**2c**	78
3	R^1=C_6H_5, R^2=H	**1d**	**A**	**2d**	12[c]
4	R^1=C_6H_5, R^2=H	**1d**	**B**[d]	**2d**	45
5	R^1=C_6H_5, R^2=H	**1d**	**B**	**2d**	78
6	R^1=4-Cl–C_6H_4, R^2=H	**1e**	**B**	**2e**	75
7	R^1=4-MeO–C_6H_4, R^2=H	**1f**	**B**	**2f**	63
8	R^1=4-Me–C_6H_4, R^2=H	**1g**	**B**	**2g**	70
9	R^1=1-Naphthyl, R^2=H	**1h**	**B**	**2h**	43
10	R^1=1-Cyclohexenyl, R^2=H	**1i**	**B**	**2i**	45
11	R^1=3-Furanyl, R^2=H	**1j**	**B**	**2j**	90
12	R^1=2-Thienyl, R^2=H	**1k**	**B**	**2k**	88
13	R^1=Me, R^2=5-F	**1l**	**B**	**2l**	64
14	R^1=Me, R^2=5-Cl	**1m**	**B**	**2m**	58
15	R^1=Me, R^2=4,5-$(MeO)_2$	**1n**	**B**	**2n**	80
16	R^1=Me, R^2=4-Me	**1o**	**B**	**2o**	82

[a] Reaction condition: **1** (0.2 mmol), anhydrous toluene (0.1 M), 100 °C, 8–12 h under Ar atmosphere; condition A: 10 mol % $Ni(COD)_2$, 20 mol % P(*i*-Pr)$_3$; condition B: 20 mol % $Ni(COD)_2$, 40 mol % P(*i*-Pr)$_3$, MS 4 Å (64 mg).
[b] Isolated yield.
[c] ^{1}H NMR yield determined using CH_2Br_2 as an internal standard.
[d] Without MS 4 Å.

in good yield (Eq. 2). It should be noted that under the standard reaction conditions other aldehydes, such as 2-(4-phenylbut-3-yn-1-yl)benzaldehyde was completely inactive without producing any six-membered ring products, aliphatic aldehyde, such as 6-phenylhex-5-ynal resulted in decomposition of the aldehyde, and the aldehyde having a terminal alkyne moiety (R^1=H) did not undergo the present hydroacylation.

The plausible Ni-catalyzed hydroacylation mechanism is shown in Scheme 1. Initially, oxidative insertion of the strong electron rich Ni(0) catalyst into C–H bond of aldehyde **1a** forms nickel acyl





Scheme 1. A plausible mechanism of Ni-catalyzed hydroacylation.

hydride **A**. The cis addition of nickel hydride to the metal-bound alkyne moiety affords the six-membered nickel acyl intermediate **B**. Reductive elimination of **B** produces the corresponding hydroacylation product **2a** as an *E*-isomer.

3. Conclusion

In conclusion, we have developed a new and efficient synthetic method for the formation of 2,3-dihydro-1*H*-inden-1-one derivatives through the Ni-catalyzed intramolecular hydroacylation of 2-(prop-2-ynyl)benzaldehydes. A wide range of functional groups are tolerated in the present catalytic hydroacylation. The use of $Ni(COD)_2/P(i\text{-}Pr)_3$ catalyst system is crucial for the efficient formation of the corresponding hydroacylation products. Further extension of this method to the synthesis of important fused aromatic compounds and application to organic electronics are in progress.

4. Experimental section

4.1. General information

^1H NMR and ^{13}C NMR spectra were recorded on JEOL JNM AL 300 (300 MHz), JEOL JNM AL 400 (400 MHz), and JEOL JNM α-500 (500 MHz) spectrometers. ^1H NMR spectra are reported as follows: chemical shift in parts per million (δ) relative to the chemical shift of $CDCl_3$ at 7.26 ppm, integration, multiplicities (s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet, and br=broadened), and coupling constants (hertz). ^{13}C NMR spectra were recorded on JEOL JNM AL 300 (75.45 MHz), JEOL JNM AL 400 (100.5 MHz), and JEOL JNM α-500 (125.65 MHz) spectrometers with complete proton decoupling, and chemical shift reported in ppm (δ) relative to the central line of triplet for $CDCl_3$ at 77 ppm. IR spectra were recorded on JASCO FT/IR-4100 spectrometer; absorptions are reported in cm^{-1}. High-resolution mass spectra were obtained on a BRUKER APEXIII spectrometer and JEOL JMS-700 MStation operator. Column chromatography was carried out employing silica gel 60 N (spherical, neutral, 40–100 μm, KANTO Chemical Co.). Analytical thin-layer chromatography (TLC) was performed on 0.2 mm precoated plate Kieselgel 60 F_{254} (Merck).

4.2. Materials

Anhydrous toluene, *o*-xylene, benzene, octane, dioxane (WAKO), $Ni(COD)_2$ (STREM), (WAKO), $Ni(CO)_2(PPh_3)_2$ (FLUKA), $[Ir(COD)Cl]_2$, $RuHCl(CO)PPh_3$, $P(t\text{-}Bu)_3$ (TCI), $P(n\text{-}Pr)_3$, $P(i\text{-}Pr)_3$, PCy_3, PMe_3, deep (ALDRICH) were purchased and used as received. 2-(Prop-2-ynyl) benzaldehydes **1** were prepared according to the literature procedure.[12] The structures of new products were determined by ^1H, ^{13}C NMR, high-resolution mass and comparing with the reported authentic compounds.[10a]

4.3. General procedure of Ni-catalyzed intramolecular hydroacylation

Condition A: synthesis of (*E*)-2-ethylidene-2,3-dihydro-1*H*-inden-1-one (**2a**): to a toluene (2 ml, 0.1 M) solution of **1a** (32 mg, 0.2 mmol), $Ni(COD)_2$ (3 mg, 10 mol %), and $P(i\text{-}Pr)_3$ (10.3 mg, 20 mol %) was stirred at 100 °C under Ar atmosphere for 18 h. After consumption of **1a**, which was monitored by TLC, the reaction mixture was filtered through a short florisil pad using diethyl ether as an eluent. After concentration, the residue was purified with silica gel chromatography to afford **2a** (27 mg, 86%) as a yellow solid.

Condition B: synthesis of (*E*)-2-benzylidene-2,3-dihydro-1*H*-inden-1-one (**2d**): to a toluene (2 ml, 0.1 M) solution of **1d** (44 mg, 0.2 mmol), $Ni(COD)_2$ (6 mg, 20 mol %), and $P(i\text{-}Pr)_3$ (20.6 mg, 40 mol %), and MS 4 Å (64 mg) was stirred at 100 °C under Ar atmosphere for 8 h. After consumption of **1d**, which was monitored by TLC, the reaction mixture was filtered through a short florisil pad using diethyl ether as an eluent. After concentration, the residue was purified with silica gel chromatography to afford **2d** (34 mg, 78%) as a yellow solid.

4.4. Analytical data of products 2

*4.4.1. (E)-2-Ethylidene-2,3-dihydro-1H-inden-1-one (**2a**).* Yellow solid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, *J*=7.6 Hz, 1H), 7.59 (t, *J*=7.6 Hz, 1H), 7.50 (d, *J*=7.6 Hz, 1H), 7.39 (t, *J*=7.6 Hz, 1H), 6.95 (qt, *J*=7.6, 2.4 Hz, 1H), 3.66 (s, 2H), 1.97 (dt, *J*=7.6, 1.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.32, 29.78, 124.3, 126.28, 127.41, 133.00, 134.34, 137.48, 138.86, 149.23, 193.13; IR (neat): 671, 741, 901, 1093, 1264, 1607, 1649, 1700, 2335, 2903 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{11}H_{11}O$, 181.0624; found, 181.0623.

*4.4.2. (E)-2-Propylidene-2,3-dihydro-1H-inden-1-one (**2b**).* Yellow solid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, *J*=7.6 Hz, 1H), 7.58 (t, *J*=7.6 Hz, 1H), 7.49 (d, *J*=7.6 Hz, 1H), 7.39 (t, *J*=7.6 Hz, 1H), 6.85 (tt, *J*=7.6, 2.0 Hz, 1H), 3.66 (s, 2H), 2.34 (t, *J*=7.6 Hz, 2H), 1.15 (t, *J*=7.6 Hz, 3H); ^{13}C NMR (100.50 MHz, $CDCl_3$) δ 12.93, 23.22, 29.78, 124.33, 126.30, 127.43, 134.39, 135.75, 138.91, 139.56, 149.36, 193.57; IR (neat): 666, 726, 748, 880, 1093, 1258, 1606, 1645, 1693, 2342, 2891, 2933, 2975 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{12}H_{12}O$, 195.0780; found, 195.0781.

*4.4.3. (E)-2-Hexylidene-2,3-dihydro-1H-inden-1-one (**2c**).* Colorless oil; ^1H NMR (500 MHz, $CDCl_3$) δ 7.84 (d, *J*=7.5 Hz, 1H), 7.56 (t, *J*=7.5 Hz, 1H), 7.47 (d, *J*=7.5 Hz, 1H), 7.37 (t, *J*=7.5 Hz, 1H), 6.87 (t, *J*=7.5 Hz, 1H), 3.64 (s, 2H), 2.29 (t, *J*=7.5 Hz, 2H), 1.54–1.52 (m, 2H), 1.33–1.31 (m, 4H), 0.88 (t, *J*=6.5 Hz, 3H), 1.15 (t, *J*=7.6 Hz, 3H); ^{13}C NMR (125.65 MHz, $CDCl_3$) δ 13.96, 22.48, 28.12, 29.85, 29.96, 31.59, 124.34, 126.28, 127.42, 134.34, 136.33, 138.42, 138.96, 149.37, 193.41; IR (neat): 671, 734, 923, 1262, 1466, 1610, 1650, 1703, 2327, 2343, 2856, 2926, 2955 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{15}H_{18}O$, 237.1250; found, 237.1250.

*4.4.4. (E)-2-Benzylidene-2,3-dihydro-1H-inden-1-one (**2d**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.91 (d, *J*=7.2 Hz, 1H), 7.69–7.66 (m, 3H), 7.62–7.56 (m, 2H), 7.46–7.40 (m, 4H), 4.04 (s, 2H); ^{13}C NMR (75.45 MHz, $CDCl_3$) δ 32.40, 124.38, 126.13, 127.62, 128.88, 129.61, 130.67, 133.87, 134.57, 134.68, 135.35, 137.97, 149.59, 194.29; IR (neat): 737, 761, 949, 1092, 1294, 1580, 1606, 1622, 1691, 2325, 2851, 2915 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{16}H_{12}O$, 243.0780; found, 243.0780.

*4.4.5. (E)-2-(4-Chlorobenzylidene)-2,3-dihydro-1H-inden-1-one (**2e**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.91 (d, *J*=7.5 Hz, 1H), 7.63–7.55 (m, 5H), 7.46–7.41 (m, 3H), 4.02 (s, 2H); ^{13}C NMR (75.45 MHz, $CDCl_3$) δ 32.34, 124.49, 126.16, 127.78, 129.20, 131.77, 132.45, 133.85, 134.76, 135.15, 135.65, 137.87, 149.40, 194.09; IR (neat): 728, 819, 1092, 1269, 1584, 1623, 1693, 2328, 2851, 2926 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{16}H_{11}ClO$, 277.0391; found, 277.0390.

*4.4.6. (E)-2-(4-Methoxybenzylidene)-2,3-dihydro-1H-inden-1-one (**2f**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.89 (d, *J*=7.5 Hz, 1H), 7.64–7.53 (m, 5H), 7.41 (t, *J*=7.5 Hz, 1H), 6.97 (d, *J*=8.7 Hz, 2H), 3.99 (s, 2H), 3.85 (s, 1H); ^{13}C NMR (75.45 MHz, $CDCl_3$) δ 32.42, 55.34, 114.41, 124.23, 126.05, 127.52, 128.10, 132.35, 132.51, 133.74, 134.28, 138.20, 149.44, 160.80, 194.31; IR (neat): 734, 822, 1023, 1255, 1514,

1600, 1691, 2318, 2343, 2840, 2926 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{17}H_{14}O_2$, 273.0886; found, 273.0885.

*4.4.7. (E)-2-(4-Methylbenzylidene)-2,3-dihydro-1H-inden-1-one (**2g**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.89 (d, J=7.5 Hz, 1H), 7.65–7.54 (m, 5H), 7.40 (t, J=7.5 Hz, 1H), 7.26–7.23 (m, 2H), 4.01 (s, 2H), 2.93 (s, 3H); ^{13}C NMR (75.45 MHz, $CDCl_3$) δ 21.49, 32.47, 124.34, 126.11, 127.58, 129.68, 130.76, 132.59, 133.72, 133.99, 134.45, 138.10, 140.14, 149.56, 194.41; IR (neat): 739, 817, 954, 1098, 1581, 1602, 1620, 1686, 2332, 2855, 2922 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{17}H_{14}O$, 257.0937; found, 257.0937.

*4.4.8. (E)-2-(Naphthalen-1-ylmethylene)-2,3-dihydro-1H-inden-1-one (**2h**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 8.46 (s, 1H), 8.23 (d, J=7.5 Hz, 1H), 7.97 (d, J=7.5 Hz, 1H), 7.91 (d, J=7.5 Hz, 2H), 7.80 (d, J=7.5 Hz, 1H), 7.62–7.44 (m, 6H), 4.01 (s, 2H); ^{13}C NMR (125.65 MHz, $CDCl_3$) δ 32.03, 124.09, 124.56, 125.21, 126.18, 126.31, 126.81, 126.94, 127.66, 128.73, 129.87, 130.93, 132.29, 132.35, 133.69, 134.64, 137.21, 138.28, 150.00, 193.90; IR (neat): 733, 768, 949, 1089, 1295, 1613, 1692, 2334, 2851, 2926, 3052 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{20}H_{14}O$, 293.0937; found, 293.0936.

*4.4.9. (E)-2-(Cyclohexenylmethylene)-2,3-dihydro-1H-inden-1-one (**2i**).* Yellow solid; ^1H NMR (500 MHz, $CDCl_3$) δ 7.87 (d, J=7.5 Hz, 1H), 7.57 (t, J=7.5 Hz, 1H), 7.49 (d, J=7.5 Hz, 1H), 7.40 (t, J=7.5 Hz, 1H), 7.24 (s, 1H), 6.38 (s, 1H), 3.95 (s, 2H), 2.49 (s, 2H), 2.27–2.26 (m, 2H), 1.76–1.73 (m, 2H), 1.65–1.63 (m, 2H); ^{13}C NMR (125.65 MHz, $CDCl_3$) δ 21.57, 22.56, 26.81, 27.15, 32.06, 124.18, 125.97, 127.36, 131.02, 134.08, 135.85, 138.11, 138.31, 140.80, 149.73, 194.68; IR (neat): 734, 930, 1092, 1266, 1579, 1605, 1686, 2321, 2851, 2926 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{16}H_{16}O$, 247.1093; found, 247.1093.

*4.4.10. (E)-2-(Furan-3-ylmethylene)-2,3-dihydro-1H-inden-1-one (**2j**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.88 (d, J=7.5 Hz, 1H), 7.81 (s, 1H), 7.63–7.51 (m, 4H), 7.44–7.39 (m, 1H), 6.72 (d, J=1.8 Hz, 1H), 3.87 (d, J=1.8 Hz, 1H); ^{13}C NMR (75.45 MHz, $CDCl_3$) δ 31.97, 110.00, 122.50, 123.99, 124.29, 126.18, 127.62, 133.95, 134.48, 138.45, 144.31, 145.75, 148.97, 193.81; IR (neat): 735, 810, 869, 1020, 1082, 1156, 1631, 1692, 2318, 2851, 2926, 3129 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{14}H_{10}O_2$, 233.0572; found, 233.0572.

*4.4.11. (E)-2-(Thiophen-2-ylmethylene)-2,3-dihydro-1H-inden-1-one (**2k**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.89–7.87 (m, 2H), 7.61–7.56 (m, 3H), 7.43–7.39 (m, 2H), 7.17–7.15 (m, 1H), 3.91 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 32.27, 124.24, 126.19, 126.51, 127.61, 128.15, 130.51, 132.69, 133.07, 134.50, 138.47, 139.84, 149.00, 193.77; IR (neat): 708, 734, 941, 1094, 1268, 1579, 1617, 1690, 2318, 2851, 2922 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{14}H_{10}OS$, 249.0345; found, 249.0345.

*4.4.12. (E)-2-Ethylidene-6-fluoro-2,3-dihydro-1H-inden-1-one (**2l**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.51–7.45 (m, 2H), 7.33–7.26 (m, 1H), 6.97 (qt, J=7.5, 2.7 Hz, 1H), 3.63 (s, 2H), 1.97 (dt, J=7.5, 2.7 Hz, 3H); ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 15.40, 29.26, 110.2 (d, J^2=21.4 Hz), 122.0 (d, J^3=13.9 Hz), 127.7 (d, J^5=7.0 Hz), 133.96, 137.8 (d, J^7=1.6 Hz), 140.6 (d, J^4=7.4 Hz), 144.6 (d, J^8=1.4 Hz), 162.5 (d, J^1=245.8 Hz), 192.2 (d, J^1=3.3 Hz); IR (neat): 757, 825, 1177, 1274, 1484, 1609, 1652, 1697, 2318, 2932, 3048 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{11}H_9FO$, 199.0530; found, 199.0529.

*4.4.13. (E)-6-Chloro-2-ethylidene-2,3-dihydro-1H-inden-1-one (**2m**).* Yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.80 (s, 1H), 7.55–7.52 (m, 1H), 7.45–7.42 (m, 1H), 6.97 (qt, J=7.2, 2.1 Hz, 1H), 3.62 (s, 2H), 1.97 (dt, J=7.2, 0.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.45, 29.43, 124.19, 127.56, 133.82, 134.17, 134.34, 137.36, 140.34, 147.25, 191.80; IR (neat): 754, 812, 1177, 1252, 1646, 1706, 2325, 2851, 2918 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{11}H_9ClO$, 215.0234; found, 215.0234.

*4.4.14. (E)-2-Ethylidene-5,6-dimethoxy-2,3-dihydro-1H-inden-1-one (**2n**).* Pale yellow solid; ^1H NMR (300 MHz, $CDCl_3$) δ 7.27 (s, 1H), 6.91 (s, 1H), 6.84 (qt, J=7.2, 2.1 Hz, 1H), 3.97 (s, 3H), 3.92 (s, 3H), 3.55 (s, 2H), 1.93 (d, J=7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.24, 29.48, 56.08, 56.19, 104.96, 107.26, 131.22, 131.82, 137.92, 144.36, 149.39, 155.15, 192.11; IR (neat): 753, 785, 837, 905, 1068, 1301, 1603, 1649, 1695, 2309, 2924 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{13}H_{14}O_3$, 241.0835; found, 241.0836.

*4.4.15. (E)-2-Ethylidene-5-methyl-2,3-dihydro-1H-inden-1-one (**2o**).* Yellow solid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.71 (d, J=7.6 Hz, 1H), 7.23 (s, 1H), 7.17 (d, J=7.6 Hz, 1H), 6.88 (qt, J=7.2, 2.0 Hz, 1H), 3.57 (s, 2H), 2.42 (s, 3H), 1.92 (d, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 15.28, 22.14, 29.64, 124.16, 126.63, 128.65, 132.39, 136.62, 137.80, 145.51, 149.71, 192.80; IR (neat): 669, 755, 891, 1113, 1322, 1609, 1646, 1698, 2318, 2851, 2922 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{12}H_{12}O$, 195.0799; found, 195.0799.

*4.4.16. (E)-2-Ethylidene-3-methoxy-2,3-dihydro-1H-inden-1-one (**2p**).* Colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, J=7.6 Hz, 1H), 7.73–7.67 (m, 2H), 7.52 (t, J=7.6 Hz, 1H), 7.18 (q, J=7.6 Hz, 1H), 5.75 (s, 1H), 3.01 (s, 3H), 2.11 (d, J=7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.84, 51.17, 74.86, 123.86, 126.23, 129.68, 134.92, 136.65, 138.42, 138.91, 148.47, 191.23; IR (neat): 746, 888, 903, 1073, 1255, 1604, 1656, 1705, 2309, 2821, 2931 cm^{-1}; HRMS (ESI): $[M+Na]^+$ calcd for $C_{12}H_{12}O_2$, 211.0730; found, 211.0729.

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Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.tet.2012.03.053. These data include MOL files and InChIKeys of the most important compounds described in this article.

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