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Synthesis of 2-Sulfenylindenones via One-Pot Tandem Meyer–Schuster Rearrangement and Radical Cyclization of Arylpropynols with Disulfides

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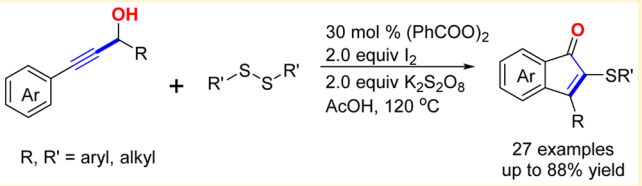
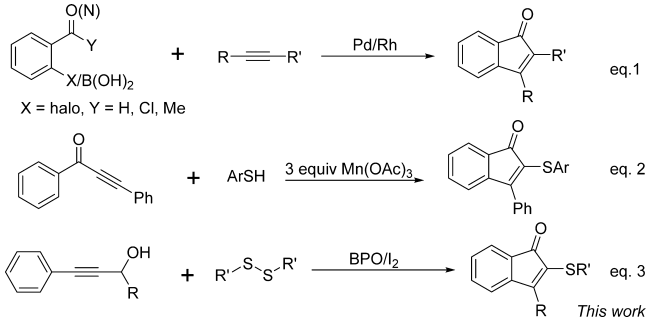
Supporting Information

ABSTRACT: A tandem annulation of arylpropynols with disulfides has been developed for the synthesis of 2-sulfenylindenone derivatives. The reaction pathway involves one-pot tandem Meyer–Schuster rearrangement of arylpropynols and successive radical cyclization with disulfides. Various arylpropynols and disulfides with a number of functional groups are compatible in this reaction that affords the corresponding 2-sulfenylindenones in moderate to good yields.



Indenones are important structural scaffolds in a great number of pharmaceuticals and biologically active molecules,[1] including alcoholic fermentation activators,[2] fungicides,[3] potential estrogen binding receptors,[4] and anticancer agents (indotecan and indimitecan).[5] Moreover, they are also versatile intermediates in the synthesis of some natural products such as steroids[6] and gibberellins.[7] Consequently, the synthesis of indenones has received much attention, and a variety of synthetic strategies have been developed for the construction of these carboncycles. Traditionally, indenone derivatives were prepared from the intramolecular Friedel–Crafts-type cyclizations or the addition of Grignard reagents to indandiones.[8] Palladium or rhodium-catalyzed annulations of internal alkynes with 2-halophenyl carbonyl compounds[9] or their equivalents[10] provided other powerful methods for the synthesis of substituted indenones (Scheme 1, eq 1). Recently, the intramolecular cyclization of 1,3-diarylpropynones triggered by superacids[11] or radicals[12] has been shown to be an efficient method for the synthesis of indenones. For example, Zou and co-workers reported a manganese-mediated addition of thiophenol to 1,3-diarylpropynones for the synthesis of thiolated indenones (eq 2).[12a] While significant progress has been made in the construction of indenone skeletons, the development of new practical and general protocol for the synthesis of diverse multisubstituted indenones is still strongly desired. As part of our continuing interest in the synthesis of sulfenylated aromatic cyclics,[13] we wish to report an iodine-mediated one-pot tandem Meyer–Schuster rearrangement and radical cyclization reaction of arylpropynols with disulfides. This reaction was conducted in a one-pot, two-step process and had greatly simplified synthetic strategies,[14] leading to 2-sulfenylindenones in moderate to good yields (eq 3).

Scheme 1. Synthesis of Indenones



We chose the model reaction between 1,3-diphenylprop-2-yn-1-ol **1a**[15] and diphenyl disulfide **2a** to optimize the reaction conditions, and the results are listed in Table 1. Initially, the reaction of substrate **1a** with diphenyl disulfide **2a**, 30 mol % benzoyl peroxide (BPO), and 2 equiv of $K_2S_2O_8$ was performed in acetic acid at 120 °C under a N_2 atmosphere, but only a trace amount of the desired product 3-phenyl-2-(phenylthio)-1*H*-inden-1-one **3** was observed (entry 1). Considering that the iodine source could promote disulfide to yield *in situ* the free radical RS$^\bullet$ or the active RSI,[13d] we subsequently investigated the reaction in the presence of 2 equiv of ICl. As expected, the product yield was dramatically increased to 61% (entry 2). Encouraged by these results, we tested various iodine sources such as $PhI(OAc)_2$, NIS, and I_2 (entries 3–5, respectively), and the results showed that I_2 provided the best results and product **3** could be isolated in 82% yield (entry 5). However, lower yields of product **3** were obtained in the absence of BPO or when AIBN or TBHP was used as an additive (entries 6–8, respectively). We next examined various oxidants, including H_2O_2, AgOTf, Ag_2CO_3, and $Cu(OAc)_2$, but all were less effective than $K_2S_2O_8$ (entries 9–12, respectively). During the screening of solvent, dioxane, DMF, $MeNO_2$, and MeCN were found to provide lower yields (entries 5 and 13–16,

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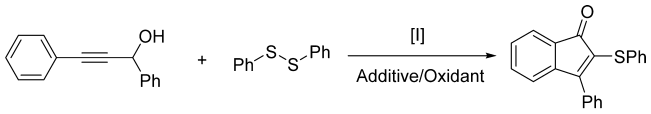
Table 1. Screening Conditions[a]



1a 2a 3

entry	I source	additive	oxidant	solvent	yield (%)[b]
1	–	BPO	$K_2S_2O_8$	AcOH	trace
2	ICl	BPO	$K_2S_2O_8$	AcOH	61
3	$PhI(OAc)_2$	BPO	$K_2S_2O_8$	AcOH	47
4	NIS	BPO	$K_2S_2O_8$	AcOH	55
5	I_2	BPO	$K_2S_2O_8$	AcOH	82
6	I_2	–	$K_2S_2O_8$	AcOH	37
7	I_2	AIBN	$K_2S_2O_8$	AcOH	56
8	I_2	TBHP	$K_2S_2O_8$	AcOH	47
9	I_2	BPO	H_2O_2	AcOH	35
10	I_2	BPO	AgOTf	AcOH	31
11	I_2	BPO	Ag_2CO_3	AcOH	37
12	I_2	BPO	$Cu(OAc)_2$	AcOH	67
13	I_2	BPO	$K_2S_2O_8$	dioxane	33
14	I_2	BPO	$K_2S_2O_8$	DMF	21
15	I_2	BPO	$K_2S_2O_8$	$MeNO_2$	74
16	I_2	BPO	$K_2S_2O_8$	MeCN	52, 60[c]
17[d]	I_2	BPO	$K_2S_2O_8$	AcOH	56

[a]Reaction conditions: **1a** (0.2 mmol), **2a** (0.2 mmol), I_2 (2 equiv), BPO (30 mol %), and $K_2S_2O_8$ (2 equiv) in HOAc (2 mL) under a N_2 atmosphere at 120 °C for 24 h. [b]Isolated yield. [c]With 5 mol % TfOH was added. [d]At 100 °C.

respectively). Meanwhile, a 74% yield of product **3** was obtained when $MeNO_2$ was used as the solvent (entry 15). In view of the results that showed that a strong acid could promote the MS rearrangement of the alkynol,[16] 5 mol % TfOH was employed in MeCN, but an only 60% yield of product **3** was obtained (entry 16). The yield was reduced to 56% when the reaction was performed at 100 °C (entry 17).

With the optimal conditions in hand, we next investigated the substrate scope of various arylpropynols and disulfides (Table 2). Initially, a wide variety of disulfides were tested, and the results demonstrated that aryl disulfides with both electron-donating and electron-withdrawing groups underwent the cyclization reaction smoothly. In general, aryl disulfides with electron-donating groups gave the products in yields higher than the yields of those bearing electron-withdrawing groups, and $MeNO_2$ was found to be a solvent that was more suitable than HOAc for some substrates with electron-withdrawing groups. For example, *p*-tolyl disulfide provided product **4** in 88% yield, while fluoride disulfides in $MeNO_2$ provided products **6**–**8** in 61, 63, and 65% yields, respectively. Similarly, chlorophenyl disulfides afforded their corresponding products **9**–**12** in 55–71% yields. Furthermore, products **13** and **14**, with the strong electron-withdrawing nitro group, were isolated in 60 and 67% yields, respectively. Gratifyingly, alkyl disulfides such as diethyl disulfide underwent the cyclization reaction successfully to give product **15** in a 54% yield.

To verify which phenyl ring was attacked in the radical cyclization, 3-phenyl-1-(*p*-tolyl)prop-2-yn-1-ol **1b** was reacted with diphenyl disulfide **2a** under standard conditions. Phenyl-cyclized product **16** was isolated in 72% yield, and tolyl cyclized product **23** could not be detected. Moreover, the structure of product **16** was confirmed by X-ray crystallography (Scheme 2). These results suggested that arylpropynols underwent a Meyer–Schuster rearrangement and then radical cyclization occurred. Subsequently, another substituent on R^2 was investigated. *o*-Tolyl provided product **17** in 55% yield, and 4-ethylphenyl afforded product **18** in 61% yield. Fluoride and chloride products **19**–**21** were obtained in 63–80% yields. It was notable that an acceptable 32% yield of **22** could be obtained when R^2 was an aliphatic cyclohexyl group. Finally, some R^1 groups at the *para* position of phenyl were investigated. Electron-donating groups such as methyl, ethyl, and *n*-butyl provided products **23**–**25** in 63–70% yields. Electron-poor fluoride, chloride, and bromide phenyl gave products **26**–**28** in slightly lower yields (51–65%). The regioselectivity was observed when *m*-chloro-substituted arylpropynol was reacted with diphenyl disulfide **2a**, and 6-position-cyclized product **29a** was isolated in 62% yield along with 2-position-cyclized **29b** in 21% yield.

To further understand this transformation, the reaction of 1,3-diphenylprop-2-yn-1-one **30** with diphenyl disulfide **2a** was conducted under the optimal reaction conditions, and only a trace amount of product **3** was observed (Scheme 3, eq 4). These results suggested that this reaction did not proceed via the oxidation of **1a** to 1,3-diarylpropynones and its subsequent intramolecular cyclization. Moreover, the reaction of substrate **1a** and diphenyl disulfide **2a** was conducted in the presence of 2.5 equiv of 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO), a radical scavenger; however, the reaction was completely restrained, and most of substrate **1a** was recovered (Scheme 3, eq 5). All of the results described above disclosed that this tandem reaction might be involved in a radical process.

On the basis of the obtained experimental results and previous reports,[12b,13d] a plausible mechanism is proposed for this reaction (Scheme 4). Propargyl alcohol is first transformed to active allenol intermediate **A** via the acid-catalyzed Meyer–Schuster rearrangement under acidic reaction conditions. In the presence of BPO and I_2, diphenyl sulfide decomposes to yield free radical $PhS^{\bullet}$, which selectively attacks the double bond of intermediate **A** to give alkyl radical **B**. Subsequently, intermediate **B** undergoes keto–enol tautomerism and intramolecular radical cyclization to generate cyclohexadienyl radical **C**. Single-electron transfer and deprotonation of cyclohexadienyl radical **C** in the presence of $K_2S_2O_8$ give dihydroindenone **D**,[17] which can be oxidized to desired product **3**.

In conclusion, we have developed an effective method for the synthesis of 2-sulfenylindenone derivatives from the iodine-mediated one-pot tandem cyclization of arylpropynols and disulfides. The reaction proceeded via a Meyer–Schuster rearrangement of arylpropynols, followed by sulfenyl radical addition to allenol and final cyclization. A variety of arylpropynols and disulfides bearing aryl or alkyl groups underwent the tandem reaction smoothly to give the corresponding 2-sulfenylindenones in moderate to good yields. This protocol would serve as a new optional route for the synthesis of 2-sulfenylindenone derivatives.

EXPERIMENTAL SECTION

General Information. Chemicals were either purchased or purified by standard techniques. ^1H NMR and ^{13}C NMR spectra were recorded on a 500 MHz spectrometer (^1H at 500 MHz, ^{13}C at 125 MHz), using $CDCl_3$ as the solvent with tetramethylsilane (TMS) as an internal standard at room temperature. Chemical shifts are given in δ relative to TMS, and the coupling constants (J) are given in hertz. High-resolution mass spectra were recorded on an ESI-Q-TOF mass

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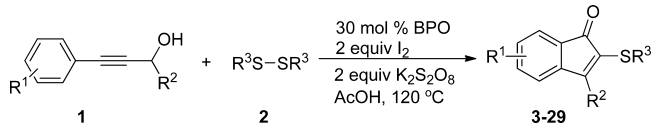
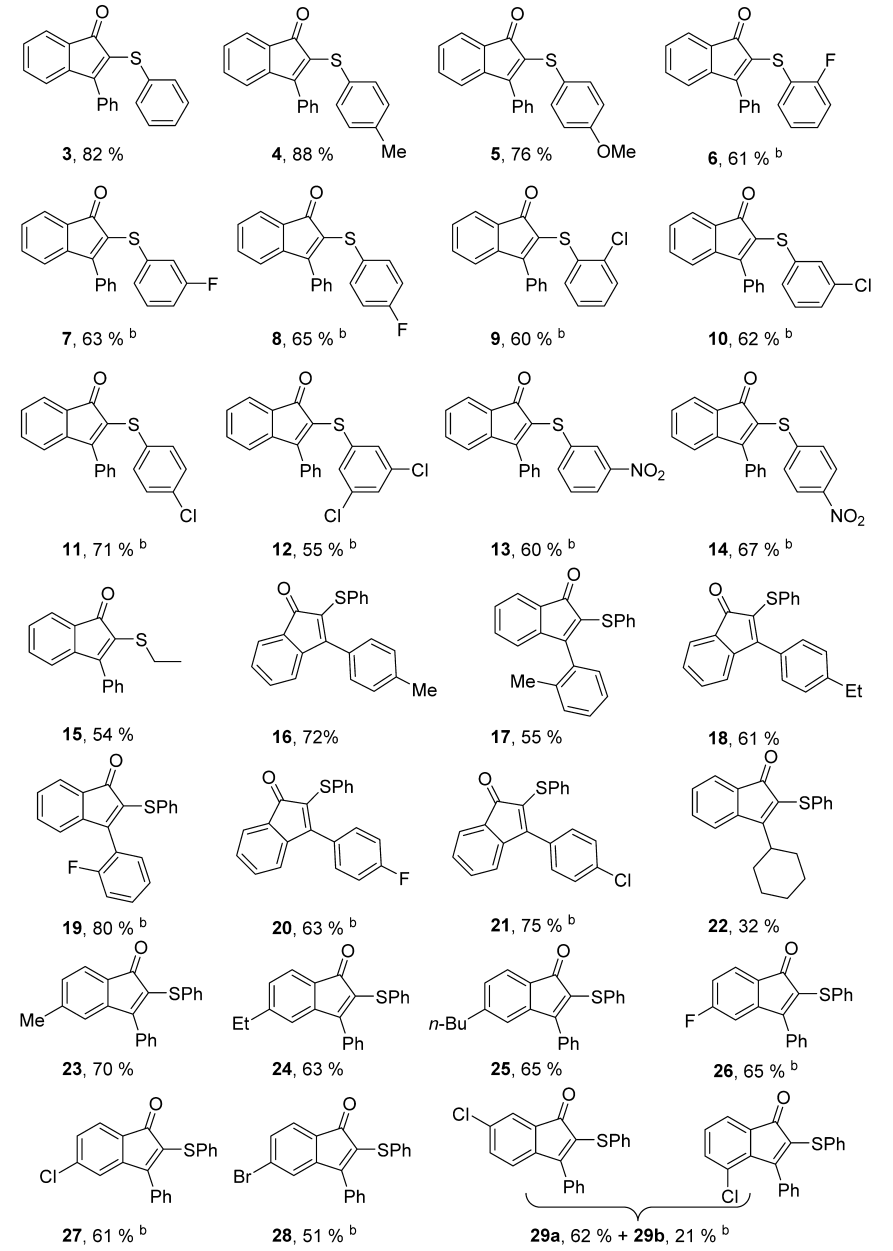
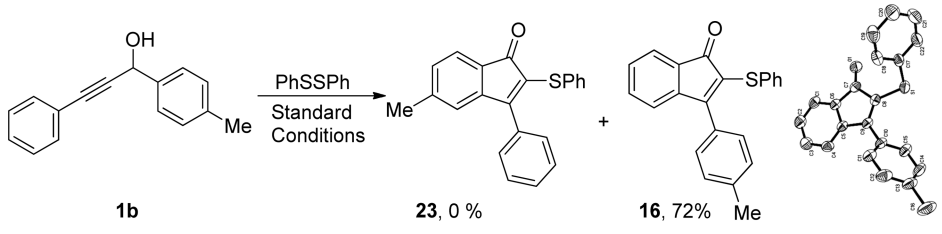
Table 2. Tandem Annulation of Arylpropynols with Disulfides[a]





[a]Reaction conditions: **1** (0.2 mmol), **2** (0.2 mmol), I_2 (2 equiv), BPO (30 mol %), and $K_2S_2O_8$ (2 equiv) in HOAc (2 mL) under a N_2 atmosphere at 120 °C for 24 h. [b]$MeNO_2$ was used as the solvent.

Scheme 2. Selective Cyclization and X-ray Structure of Compound 16



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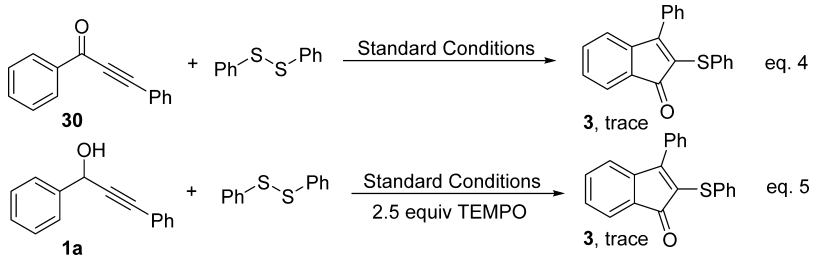
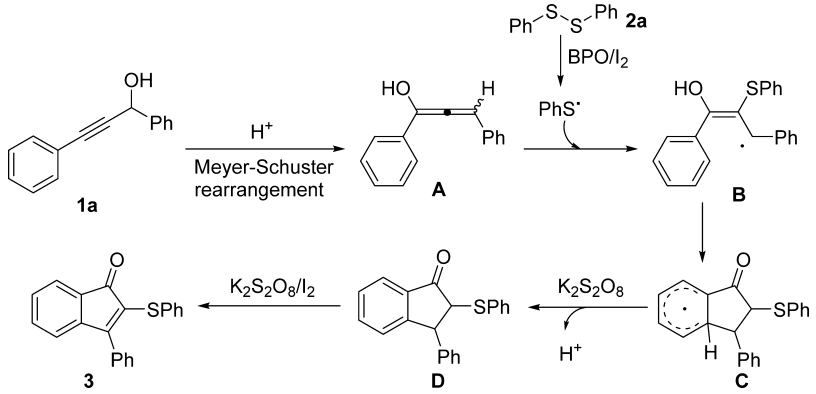
Scheme 3. Control Experiment



Scheme 4. Possible Mechanism



spectrometer. All reactions under a nitrogen atmosphere were conducted using standard Schlenk techniques. Melting point data are uncorrected. Column chromatography was performed using EM silica gel 60 (300−400 mesh).

Typical Experimental Procedure for the Synthesis of Arylpropynol.[15] To a solution of alkyne (13 mmol) in anhydrous THF (30 mL) at −78 °C under a N_2 atmosphere was added *n*-BuLi (1.6 mol in hexanes, 6.9 mL, 11 mmol). The reaction mixture was stirred at this temperature for 20 min and then at room temperature for 1 h. After the mixture had been cooled to −78 °C, aldehyde (10 mmol) was added to the mixture and the mixture allowed to warm to room temperature gradually and stirred for an additional 1 h before the reaction was quenched with aqueous NH_4Cl. The mixture was extracted with EtOAc (3 × 10 mL), and the combined oganic phases were washed with water and brine, dried with anhydrous $MgSO_4$, and filtered. The filtrate was concentrated under pressure, and the residue was purified by flash chromatography on silica gel [15:1 (v/v) hexanes/ethyl acetal] to produce the desired alcohol as a yellow oil.

General Procedure for the Synthesis of Thiolated Indenones. Under a N_2 atmosphere, an oven-dried reaction vessel was charged with 1,3-diarylpropynones **1** (0.2 mmol), disulfides **2** (0.2 mmol), $K_2S_2O_8$ (0.4 mmol), I_2 (0.4 mmol), BPO (0.06 mmol), and AcOH (2 mL). The vessel was sealed and heated at 120 °C for 24 h and then cooled to room temperature. The mixture was cleaned with a saturated $Na_2S_2O_4$ solution three times and extracted with ethyl acetate three times, and the combined organic layer was dried over anhydrous $MgSO_4$. After removal of the solvent under reduced pressure, the residue was purified by silica gel column chromatography [50:1 (v/v) petroleum ether (bp 60−90 °C)/EtOAc gradients] to give products **3**−**29**.

3-Phenyl-2-(phenylthio)-1H-inden-1-one (***3***).[12a] Red solid (51.6 mg, 82% yield): mp 125−127 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.52 (d, J = 7.0 Hz, 1H), 7.50−7.46 (m, 3H), 7.39−7.36 (m, 1H), 7.29−7.24 (m, 3H), 7.20−7.17 (m, 3H), 7.14−7.11 (m, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.2, 162.0, 144.5, 134.8, 133.8, 131.8, 131.1, 130.3, 129.5, 129.3, 129.0, 128.7, 128.6, 127.4, 126.5, 123.5, 121.8; LRMS (EI, 70 eV) m/z (%) 314 (M^+, 100), 165 (43), 313, 221 (29), 237 (27).

3-Phenyl-2-(p-tolylthio)-1H-inden-1-one (***4***). Red solid (57.8 mg, 88% yield): mp 154−156 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.58 (d, J = 7.0 Hz, 2H), 7.50−7.46 (m, 4H), 7.38−7.35 (m, 1H), 7.28−7.25 (m, 1H), 7.20−7.17 (m, 3H), 7.01 (d, J = 7.5 Hz, 2H), 2.26 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.3, 161.0, 144.6, 136.7, 133.7, 131.9, 131.1, 130.8, 130.2, 129.9, 129.8, 129.3, 128.63, 128.62, 128.0, 123.5, 121.6, 21.2; LRMS (EI, 70 eV) m/z (%) 328 (M^+, 100), 165 (30), 300 (29), 327 (27), 329 (26); HRMS (ESI) calcd for $C_{22}H_{17}OS^+$ ([M + H]$^+$) 329.0995, found 329.0989.

2-[(4-Methoxyphenyl)thio]-3-phenyl-1H-inden-1-one (***5***). Red solid (52.4 mg, 76% yield): mp 136−137 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.58−7.56 (m, 2H), 7.51−7.47 (m, 4H), 7.36−7.34 (m, 1H), 7.28−7.23 (m, 3H), 7.15 (d, J = 7.5 Hz, 1H), 6.75 (d, J = 8.5 Hz, 2H), 3.75 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.5, 159.7, 159.2, 144.7, 133.7, 132.7, 131.9, 131.0, 130.1, 129.2, 128.9, 128.7, 128.6, 124.3, 123.4, 121.4, 114.7, 55.4; LRMS (EI, 70 eV) m/z (%) 344 (M^+, 100), 345 (24), 151 (23), 343 (22), 165 (20); HRMS (ESI) calcd for $C_{22}H_{17}O_2S^+$ ([M + H]$^+$) 345.0944, found 345.0963.

2-[(2-Fluorophenyl)thio]-3-phenyl-1H-inden-1-one (***6***). Red solid (40.6 mg, 61% yield): mp 106−107 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59−7.58 (m, 2H), 7.50−7.44 (m, 4H), 7.36−7.35 (m, 1H), 7.29−7.25 (m, 2H), 7.17−7.12 (m, 2H), 7.00−6.94 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.8, 160.9 (d, $^1J_{CF}$ = 245.0 Hz), 160.7, 144.5, 133.8, 132.3, 131.6, 131.1, 130.2, 129.3, 128.8 (d, $^3J_{CF}$ = 8.8 Hz), 128.6, 128.5, 126.3, 124.5 (d, $^4J_{CF}$ = 3.8 Hz), 123.5, 121.6, 121.1 (d, $^2J_{CF}$ = 16.3 Hz), 115.8 (d, $^2J_{CF}$ = 21.3 Hz); LRMS (EI, 70 eV) m/z (%) 332 (M^+, 100), 221 (44), 165 (41), 176 (26), 333 (24); HRMS (ESI) calcd for $C_{21}H_{14}FOS^+$ ([M + H]$^+$) 333.0744, found 333.0756.

2-[(3-Fluorophenyl)thio]-3-phenyl-1H-inden-1-one (***7***). Red solid (41.9 mg, 63% yield): mp 112−114 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.60−7.58 (m, 2H), 7.56 (d, J = 7.5 Hz, 1H), 7.53−7.49 (m, 3H), 7.43−7.40 (m, 1H), 7.34−7.31 (m, 1H), 7.23 (d, J = 7.0 Hz, 1H), 7.19−7.15 (m, 1H), 7.06−7.05 (m, 1H), 6.98−6.95 (m, 1H), 6.85−6.81 (m, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.9, 162.9 (d, $^1J_{CF}$ = 246.3 Hz), 163.0, 144.3, 137.3 (d, $^3J_{CF}$ = 7.5 Hz), 133.9, 131.6, 131.1, 130.5, 130.2 (d, $^3J_{CF}$ = 8.8 Hz), 129.8, 128.7, 128.6, 126.3, 124.6, 123.7, 122.0, 115.9 (d, $^2J_{CF}$ = 23.8 Hz), 113.5 (d, $^2J_{CF}$ = 21.3 Hz); LRMS (EI, 70 eV) m/z (%) 332 (M^+, 60), 207 (100), 331 (70), 281 (45), 73 (42); HRMS (ESI) calcd for $C_{21}H_{14}FOS^+$ ([M + H]$^+$) 333.0744, found 333.0753.

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*2-[(4-Fluorophenyl)thio]-3-phenyl-1H-inden-1-one (**8**).* Red solid (43.3 mg, 65% yield): mp 172−174 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.57−7.55 (m, 2H), 7.52−7.48 (m, 4H), 7.38−7.35 (m, 1H), 7.29−7.25 (m, 3H), 7.17 (d, J = 7.5 Hz, 1H), 6.92−6.87 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.2, 162.1 (d, $^1J_{CF}$ = 245.0 Hz), 161.0, 144.5, 133.8, 132.2 (d, $^3J_{CF}$ = 7.5 Hz), 131.8, 131.0, 130.3, 129.5, 129.3, 128.7, 128.6, 127.9, 123.5, 121.7, 116.1 (d, $^2J_{CF}$ = 22.5 Hz); LRMS (EI, 70 eV) m/z (%) 332 (M^+, 100), 165 (44), 304 (34), 139 (31), 333 (30); HRMS (ESI) calcd for $C_{21}H_{14}FOS^+$ ([M + H]$^+$) 333.0744, found 333.0755.

*2-[(2-Chlorophenyl)thio]-3-phenyl-1H-inden-1-one (**9**).* Red solid (41.9 mg, 60% yield): mp 156−158 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.53−7.48 (m, 3H), 7.45−7.40 (m, 3H), 7.36−7.33 (m, 1H), 7.27−7.22 (m, 2H), 7.16 (d, J = 7.5 Hz, 1H), 7.10−7.08 (m, 1H), 7.03−6.99 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.7, 162.8, 144.4, 134.2, 133.8, 133.3, 131.6, 131.1, 130.4, 130.1, 129.9, 129.6, 128.7, 128.5, 127.3, 127.1, 126.0, 123.6, 121.9; LRMS (EI, 70 eV) m/z (%) 348 (M^+, 33), 313 (100), 207 (36), 165 (25), 314 (24); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ([M + H]$^+$) 349.0448, found 349.0454.

*2-[(3-Chlorophenyl)thio]-3-phenyl-1H-inden-1-one (**10**).* Red solid (43.3 mg, 62% yield): mp 135−137 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59−7.55 (m, 3H), 7.51−7.50 (m, 3H), 7.42−7.39 (m, 1H), 7.33−7.31 (m, 1H), 7.26−7.23 (m, 2H), 7.17−7.09 (m, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.9, 162.7, 144.3, 136.9, 134.8, 133.9, 131.6, 131.0, 130.5, 130.0, 129.7, 128.7, 128.5, 127.7, 127.2, 126.7, 126.3, 123.7, 122.0; LRMS (EI, 70 eV) m/z (%) 348 (M^+, 100), 165 (64), 221 (40), 350 (39), 284 (34); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ([M + H]$^+$) 349.0448, found 349.0444.

*2-[(4-Chlorophenyl)thio]-3-phenyl-1H-inden-1-one (**11**).* Red solid (49.5 mg, 71% yield): mp 135−136 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.54−7.49 (m, 4H), 7.41−7.38 (m, 1H), 7.32−7.29 (m, 1H), 7.22−7.20 (m, 3H), 7.18−7.16 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.0, 162.0, 144.4, 133.8, 133.2, 132.7, 131.7, 131.0, 130.8, 130.4, 129.6, 129.1, 128.7, 128.6, 127.0, 123.6, 121.8; LRMS (EI, 70 eV) m/z (%) 348 (M^+, 24), 207 (100), 281 (43), 208 (26), 341 (20); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ([M + H]$^+$) 349.0448, found 349.0448.

*2-[(3,5-Dichlorophenyl)thio]-3-phenyl-1H-inden-1-one (**12**).* Red oil (42.2 mg, 55% yield): ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.58−7.56 (m, 3H), 7.52−7.49 (m, 3H), 7.44−7.41 (m, 1H), 7.36−7.33 (m, 1H), 7.26−7.23 (m, 1H), 7.10 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.6, 163.5, 144.2, 138.5, 135.3, 134.0, 131.4, 131.0, 130.7, 130.0, 128.8, 128.5, 126.9, 126.7, 125.3, 123.8, 122.2; LRMS (EI, 70 eV) m/z (%) 382 (M^+, 100), 165 (99), 384 (71), 221 (59), 176 (41); HRMS (ESI) calcd for $C_{21}H_{13}Cl_2OS^+$ ([M + H]$^+$) 383.0059, found 383.0053.

*2-[(3-Nitrophenyl)thio]-3-phenyl-1H-inden-1-one (**13**).* Red solid (43.1 mg, 60% yield): mp 124−126 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.05 (s, 1H), 7.97−7.95 (m, 1H), 7.60−7.57 (m, 3H), 7.55 (d, J = 7.0 Hz, 1H), 7.52−7.49 (m, 3H), 7.44−7.41 (m, 1H), 7.39−7.32 (m, 2H), 7.25−7.24 (m, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.7, 163.3, 148.6, 144.2, 137.7, 134.6, 134.1, 131.4, 130.9, 130.7, 130.0, 129.6, 128.8, 128.5, 125.3, 123.8, 123.6, 122.2, 121.3; LRMS (EI, 70 eV) m/z (%) 359 (M^+, 100), 165 (64), 221 (42), 284 (25), 360 (24); HRMS (ESI) calcd for $C_{21}H_{14}NO_3S^+$ ([M + H]$^+$) 360.0689, found 360.0697.

*2-[(4-Nitrophenyl)thio]-3-phenyl-1H-inden-1-one (**14**).* Yellow solid (48.2 mg, 67% yield): mp 187−189 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.99 (d, J = 8.5 Hz, 2H), 7.52−7.45 (m, 6H), 7.40−7.29 (m, 2H), 7.26−7.21 (m, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.4, 165.0, 146.0, 145.4, 144.0, 134.1, 131.3, 131.0, 130.3, 128.9, 128.5, 127.8, 126.7, 124.6, 124.1, 123.9, 122.5; LRMS (EI, 70 eV) m/z (%) 359 (M^+, 100), 165 (53), 221 (40), 360 (24), 284 (21); HRMS (ESI) calcd for $C_{21}H_{14}NO_3S^+$ ([M + H]$^+$) 360.0689, found 360.0695.

*2-(Ethylthio)-3-phenyl-1H-inden-1-one (**15**).* Red solid (28.8 mg, 54% yield): mp 92−94 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.58−7.55 (m, 2H), 7.54−7.47 (m, 4H), 7.34−7.31 (m, 1H), 7.23−7.20 (m, 1H), 7.08 (d, J = 7.5 Hz, 1H), 3.02 (q, J = 7.5 Hz, 2H), 1.20 (t, J = 7.5 Hz, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 194.4, 157.2, 145.1, 133.8, 132.4, 131.4, 129.8, 129.4, 128.7, 128.6, 128.5, 123.2, 120.7, 26.6, 15.5; LRMS (EI, 70 eV) m/z (%) 266 (M^+, 59), 233 (100), 165 (82), 215 (33), 237 (27); HRMS (ESI) calcd for $C_{17}H_{15}OS^+$ ([M + H]$^+$) 267.0838, found 267.0845.

*2-(Phenylthio)-3-(p-tolyl)-1H-inden-1-one (**16**).* Red solid (47.3 mg, 72% yield): mp 84−86 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.52−7.50 (m, 3H), 7.39−7.36 (m, 1H), 7.31−7.28 (m, 4H), 7.24−7.18 (m, 4H), 7.14−7.11 (m, 1H), 2.42 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.3, 162.5, 144.5, 140.8, 135.2, 133.7, 131.3, 129.5, 129.4, 129.2, 129.0, 128.9, 128.7, 126.7, 126.4, 123.4, 121.8, 21.7; LRMS (EI, 70 eV) m/z (%) 328 (M^+, 100), 313 (29), 329, 327 (27), 121 (25); HRMS (ESI) calcd for $C_{22}H_{17}OS^+$ ([M + H]$^+$) 329.0995, found 329.1010.

*2-(Phenylthio)-3-(o-tolyl)-1H-inden-1-one (**17**).* Red solid (36.1 mg, 55% yield): mp 125−127 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.52−7.50 (m, 1H), 7.32−7.30 (m, 2H), 7.27−7.23 (m, 5H), 7.19−7.11 (m, 4H), 6.77 (d, J = 7.0 Hz, 1H), 2.26 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.2, 162.4, 145.4, 135.9, 134.1, 133.7, 131.8, 130.7, 130.5, 130.4, 129.6, 129.4, 129.3, 128.9, 128.0, 126.9, 126.0, 123.3, 121.4, 20.3; LRMS (EI, 70 eV) m/z (%) 328 (M^+, 100), 219 (78), 189 (31), 191 (28), 329 (26); HRMS (ESI) calcd for $C_{22}H_{17}OS^+$ ([M + H]$^+$) 329.0995, found 329.0990.

*3-(4-Ethylphenyl)-2-(phenylthio)-1H-inden-1-one (**18**).*[12a] Red solid (41.8 mg, 61% yield): mp 91−93 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.54−7.51 (m, 3H), 7.39−7.36 (m, 1H), 7.32 (d, J = 7.5 Hz, 2H), 7.30−7.23 (m, 4H), 7.21−7.18 (m, 2H), 7.14−7.11 (m, 1H), 2.72 (q, J = 7.5 Hz, 2H), 1.28 (t, J = 7.5 Hz, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.3, 162.3, 147.0, 144.6, 135.1, 133.6, 131.3, 129.5, 129.2, 129.0, 128.8, 128.2, 127.9, 126.7, 126.4, 123.4, 121.9, 29.1, 15.4; LRMS (EI, 70 eV) m/z (%) 342 (M^+, 100), 313 (75), 314 (29), 343 (26), 121 (25).

*3-(2-Fluorophenyl)-2-(phenylthio)-1H-inden-1-one (**19**).* Red solid (53.2 mg, 80% yield): mp 132−134 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.50 (d, J = 7.0 Hz, 1H), 7.43−7.39 (m, 2H), 7.36−7.33 (m, 1H), 7.29 (d, J = 7.5 Hz, 2H), 7.25−7.20 (m, 2H), 7.18−7.11 (m, 4H), 6.96 (d, J = 7.5 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.7, 159.9 (d, $^1J_{CF}$ = 248.8 Hz), 155.6, 144.6, 134.1, 133.6, 131.7 (d, $^3J_{CF}$ = 7.5 Hz), 130.9, 130.4, 130.3, 130.2, 129.3, 128.9, 128.0, 126.9, 124.3, 123.4, 121.4, 116.4 (d, $^2J_{CF}$ = 21.3 Hz); LRMS (EI, 70 eV) m/z (%) 332 (M^+, 100), 183 (36), 333 (23), 237, 331 (18); HRMS (ESI) calcd for $C_{21}H_{14}FOS^+$ ([M + H]$^+$) 333.0744, found 333.0740.

*3-(4-Fluorophenyl)-2-(phenylthio)-1H-inden-1-one (**20**).* Red solid (41.9 mg, 63% yield): mp 131−133 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.52 (d, J = 7.0 Hz, 1H), 7.40−7.37 (m, 1H), 7.30−7.24 (m, 3H), 7.20−7.16 (m, 4H), 7.15−7.11 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.0, 163.8 (d, $^1J_{CF}$ = 250 Hz), 160.6, 144.4, 136.7, 134.5, 133.8, 131.1, 130.8 (d, $^3J_{CF}$ = 8.8 Hz), 129.6, 129.5, 129.4, 129.1, 126.7, 123.6, 121.5, 115.9 (d, $^2J_{CF}$ = 21.3 Hz); LRMS (EI, 70 eV) m/z (%) 332 (M^+, 100), 183 (31), 239 (30), 331 (27), 255 (26); HRMS (ESI) calcd for $C_{21}H_{14}FOS^+$ ([M + H]$^+$) 333.0744, found 333.0750.

*3-(4-Chlorophenyl)-2-(phenylthio)-1H-inden-1-one (**21**).* Red solid (52.3 mg, 75% yield): mp 85−87 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.54−7.53 (m, 3H), 7.47−7.46 (m, 2H), 7.41−7.38 (m, 1H), 7.31−7.27 (m, 3H), 7.22−7.19 (m, 2H), 7.17−7.14 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 192.8, 160.2, 144.2, 136.7, 136.3, 134.3, 133.9, 131.0, 130.2, 130.0, 129.6, 129.1, 129.0, 128.1, 126.8, 123.7, 121.4; LRMS (EI, 70 eV) m/z (%) 348 (M^+, 100), 350 (41), 320, 284 (38), 163 (32); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ([M + H]$^+$) 349.0448, found 349.0452.

*3-Cyclohexyl-2-(phenylthio)-1H-inden-1-one (**22**).* Yellow solid (20.5 mg, 32% yield): mp 90−92 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.46 (d, J = 7.0 Hz, 1H), 7.41−7.38 (m, 2H), 7.29−7.26 (m, 3H), 7.25−7.22 (m, 2H), 7.16−7.13 (m, 1H), 3.22−3.16 (m, 1H), 1.97−1.86 (m, 4H), 1.82−1.75 (m, 3H), 1.43−1.34 (m, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 193.7, 172.3, 143.6, 135.9, 133.6, 131.5, 129.4, 129.1, 128.6, 126.2, 126.1, 123.1, 121.7, 39.9, 30.0, 26.3, 26.1; LRMS (EI, 70 eV) m/z (%) 320 (M^+, 100), 143 (32), 115 (29), 321, 211 (24); HRMS (ESI) calcd for $C_{21}H_{21}OS^+$ ([M + H]$^+$) 321.1308, found 321.1308.

*5-Methyl-3-phenyl-2-(phenylthio)-1H-inden-1-one (**23**).* Red solid (46.0 mg, 70% yield): mp 130−132 °C; ^{1}H NMR (500 MHz, $CDCl_3$)

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δ 7.59−7.57 (m, 2H), 7.52−7.48 (m, 3H), 7.43 (d, J = 7.5 Hz, 1H), 7.28−7.26 (m, 2H), 7.22−7.18 (m, 2H), 7.15−7.12 (m, 1H), 7.10−7.08 (m, 1H), 7.01 (s, 1H), 2.36 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 192.9, 161.8, 145.0, 144.8, 135.0, 132.0, 130.2, 129.5, 129.2, 129.0, 128.7, 128.6, 128.5, 127.7, 126.5, 123.7, 123.0, 22.2; LRMS (EI, 70 eV) *m*/*z* (%) 328 (M^+, 100), 300 (39), 329 (26), 327, 251 (23); HRMS (ESI) calcd for $C_{22}H_{17}OS^+$ ($[M + H]^+$) 329.0995, found 329.0993.

5-Ethyl-3-phenyl-2-(phenylthio)-1H-inden-1-one (**24**). Red solid (43.1 mg, 63% yield): mp 119−121 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.59−7.58 (m, 2H), 7.53−7.48 (m, 3H), 7.46 (d, J = 7.5 Hz, 1H), 7.28−7.26 (m, 2H), 7.21−7.18 (m, 2H), 7.15−7.11 (m, 2H), 7.03 (s, 1H), 2.65 (q, J = 8.0 Hz, 2H), 1.23 (t, J = 8.0 Hz, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 192.9, 161.9, 151.2, 145.0, 135.0, 132.0, 130.2, 129.2, 129.0, 128.9, 128.8, 128.6, 128.4, 127.7, 126.4, 123.8, 122.0, 26.9, 15.4; LRMS (EI, 70 eV) *m*/*z* (%) 342 (M^+, 100), 314 (38), 313 (31), 343 (27), 299 (23); HRMS (ESI) calcd for $C_{23}H_{19}OS^+$ ($[M + H]^+$) 343.1151, found 343.1160.

5-Butyl-3-phenyl-2-(phenylthio)-1H-inden-1-one (**25**). Red solid (48.2 mg, 65% yield): mp 73−75 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.59−7.57 (m, 2H), 7.52−7.47 (m, 3H), 7.44 (d, J = 7.5 Hz, 1H), 7.28−7.25 (m, 2H), 7.21−7.18 (m, 2H), 7.14−7.08 (m, 2H), 7.00 (s, 1H), 2.60 (t, J = 8.0 Hz, 2H), 1.59−1.55 (m, 2H), 1.38−1.33 (m, 2H), 0.92 (t, J = 7.5 Hz, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 192.9, 161.9, 149.9, 144.9, 135.0, 132.0, 130.1, 129.3, 129.0, 128.9, 128.8, 128.7, 128.6, 127.7, 126.5, 123.7, 122.4, 36.3, 33.4, 22.5, 14.0; LRMS (EI, 70 eV) *m*/*z* (%) 370 (M^+, 100), 313 (34), 371 (33), 299, 207 (25); HRMS (ESI) calcd for $C_{25}H_{23}OS^+$ ($[M + H]^+$) 371.1464, found 371.1467.

5-Fluoro-3-phenyl-2-(phenylthio)-1H-inden-1-one (**26**). Red solid (43.2 mg, 65% yield): mp 159−161 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.57−7.55 (m, 2H), 7.52−7.48 (m, 4H), 7.30−7.28 (m, 2H), 7.22−7.19 (m, 2H), 7.17−7.14 (m, 1H), 6.94−6.91 (m, 2H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 191.3, 166.6 (d, $^1J_{CF}$ = 253.8 Hz), 158.7, 147.9, 134.0, 131.4, 130.4, 129.9, 129.5, 129.1, 128.8, 128.5, 127.0, 126.9, 125.4 (d, $^3J_{CF}$ = 10.0 Hz), 114.9 (d, $^2J_{CF}$ = 22.5 Hz), 110.5 (d, $^2J_{CF}$ = 26.3 Hz); LRMS (EI, 70 eV) *m*/*z* (%) 332 (M^+, 100), 183 (31), 239 (30), 331 (27), 255 (26); HRMS (ESI) calcd for $C_{21}H_{14}FOS^+$ ($[M + H]^+$) 333.0744, found 333.0749.

5-Chloro-3-phenyl-2-(phenylthio)-1H-inden-1-one (**27**). Red solid (42.6 mg, 61% yield): mp 151−153 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.56−7.55 (m, 2H), 7.52−7.48 (m, 3H), 7.44 (d, J = 8.0 Hz, 1H), 7.28−7.24 (m, 3H), 7.22−7.19 (m, 2H), 7.17−7.13 (m, 2H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 191.7, 159.6, 146.4, 140.2, 134.0, 131.3, 130.5, 129.8, 129.3, 129.2, 129.1, 128.9, 128.8, 128.5, 126.9, 124.4, 122.3; LRMS (EI, 70 eV) *m*/*z* (%) 348 (M^+, 100), 350 (42), 284 (36), 255 (34), 349 (32); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ($[M + H]^+$) 349.0448, found 349.0444.

5-Bromo-3-phenyl-2-(phenylthio)-1H-inden-1-one (**28**). Red solid (40.1 mg, 51% yield): mp 140−141 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.61−7.59 (m, 2H), 7.54 (d, J = 7.0 Hz, 1H), 7.50−7.49 (m, 2H), 7.41−7.38 (m, 1H), 7.31−7.27 (m, 3H), 7.22−7.19 (m, 3H), 7.15−7.13 (m, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 193.2, 162.0, 144.6, 134.8, 133.8, 131.9, 131.1, 130.3, 129.5, 129.4, 129.0, 128.7, 128.6, 127.4, 126.6, 123.6, 121.8; LRMS (EI, 70 eV) *m*/*z* (%) 394/392 (M^+, 100), 284 (60), 163 (59), 313 (52); HRMS (ESI) calcd for $C_{21}H_{14}BrOS^+$ ($[M + H]^+$) 392.9943, found 392.9945.

6-Chloro-3-phenyl-2-(phenylthio)-1H-inden-1-one (**29a**). Red solid (43.3 mg, 62% yield): mp 109−111 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.58−7.56 (m, 2H), 7.52−7.49 (m, 3H), 7.47 (s, 1H), 7.35 (d, J = 8.0 Hz, 1H), 7.28−7.25 (m, 2H), 7.22−7.19 (m, 2H), 7.16−7.13 (m, 2H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 191.9, 161.3, 142.6, 135.8, 134.3, 133.0, 132.7, 131.4, 130.6, 129.6, 129.1, 128.8, 128.5, 127.7, 126.8, 124.1, 122.6; LRMS (EI, 70 eV) *m*/*z* (%) 348 (M^+, 100), 255 (54), 284 (40), 350 (36), 176 (29); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ($[M + H]^+$) 349.0448, found 349.0471.

4-Chloro-3-phenyl-2-(phenylthio)-1H-inden-1-one (**29b**). Red solid (14.7 mg, 21% yield): mp 142−144 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 7.45−7.41 (m, 4H), 7.39−7.37 (m, 2H), 7.29−7.28 (m, 1H), 7.27−7.26 (m, 2H), 7.23−7.20 (m, 3H), 7.19−7.17 (m, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 191.7, 162.6, 139.9, 136.8, 133.9, 133.1, 132.9, 131.7, 130.7, 130.3, 129.4, 129.0, 128.7, 128.3, 128.2, 127.0, 121.9; LRMS (EI, 70 eV) *m*/*z* (%) 348 (M^+, 100), 350 (38), 284 (37), 349 (31), 121 (28); HRMS (ESI) calcd for $C_{21}H_{14}ClOS^+$ ($[M + H]^+$) 349.0448, found 349.0468.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00762.

Copies of ^1H and ^{13}C NMR spectra for products **3**−**29** (PDF)

X-ray data for compound **16** (CIF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Ahn, J. H.; Shin, M. S.; Jung, S. H.; Kang, S. K.; Kim, K. R.; Rhee, S. D.; Jung, W. H.; Yang, S. D.; Kim, S. J.; Woo, J. R.; Lee, J. H.; Cheon, H. G.; Kim, S. S. *J. Med. Chem.* **2006**, *49*, 4781. (b) Saxena, H. O.; Faridi, U.; Srivastava, S.; et al. *Bioorg. Med. Chem. Lett.* **2008**, *18*, 3914. (c) Hatcher, J. M.; Weisberg, E.; Sim, T.; Stone, R. M.; Liu, S.; Griffin, J. D.; Gray, N. S. *ACS Med. Chem. Lett.* **2016**, *7*, 476. (d) Anstead, G. M.; Altenbach, R. J.; Wilson, S. R.; Katzenellenbogen, J. A. *J. Med. Chem.* **1988**, *31*, 1316.

(2) Frank, R. L.; Eklund, H.; Richter, J. W.; Vanneman, C. R.; Wennerberg, A. N. *J. Am. Chem. Soc.* **1944**, *66*, 1.

(3) Jourdan, G. P.; Dreikorn, B. A.; Hackler, R. E.; Hall, H. R.; Arnold, W. R. In *Synthesis and Chemistry of Agrochemicalals II*; ACS Symposium Series; American Chemical Society: Washington, DC, 1991; p 566.

(4) Anstead, G. M.; Ensign, J. L.; Peterson, C. S.; Katzenellenbogen, J. A. *J. Org. Chem.* **1989**, *54*, 1485.

(5) (a) Beck, D. E.; Reddy, P. V. N.; Lv, W.; Abdelmalak, M.; Tender, G. S.; Lopez, S.; Agama, K.; Marchand, C.; Pommier, Y.; Cushman, M. *J. Med. Chem.* **2016**, *59*, 3840. (b) Lv, P.-C.; Elsayed, M. S. A.; Agama, K.; Marchand, C.; Pommier, Y.; Cushman, M. *J. Med. Chem.* **2016**, *59*, 4890. (c) Nagarajan, M.; Morrell, A.; Ioanoviciu, A.; Antony, S.; Kohlhagen, G.; Agama, K.; Hollingshead, M.; Pommier, Y.; Cushman, M. *J. Med. Chem.* **2006**, *49*, 6283.

(6) Chatterjee, A.; Banerjee, S. *Tetrahedron* **1970**, *26*, 2599.

(7) House, H. O.; Larson, J. K. *J. Org. Chem.* **1968**, *33*, 448.

(8) (a) Floyd, M. B.; Allen, G. R., Jr *J. Org. Chem.* **1970**, *35*, 2647. (b) Galatsis, P.; Manwell, J. J.; Blackwell, J. M. *Can. J. Chem.* **1994**, *72*, 1656.

(9) (a) Kokubo, K.; Matsumasa, K.; Miura, M.; Nomura, M. *J. Org. Chem.* **1996**, *61*, 6941. (b) Larock, R. C.; Doty, M. J.; Cacchi, S. *J. Org. Chem.* **1993**, *58*, 4579. (c) Pletnev, A. A.; Tian, Q.; Larock, R. C. *J. Org. Chem.* **2002**, *67*, 9276.

(10) (a) Kundu, K.; McCullagh, J. V.; Morehead, A. T., Jr *J. Am. Chem. Soc.* **2005**, *127*, 16042. (b) Larock, R. C.; Tian, Q.; Pletnev, A. A. *J. Am. Chem. Soc.* **1999**, *121*, 3238. (c) Morimoto, T.; Yamasaki, K.; Hirano, A.; Tsutsumi, K.; Kagawa, N.; Kakiuchi, K.; Harada, Y.; Fukumoto, Y.; Chatani, N.; Nishioka, T. *Org. Lett.* **2009**, *11*, 1777.

DOI: 10.1021/acs.joc.6b00762
J. Org. Chem. 2016, 81, 5710−5716

(d) Miura, T.; Murakami, M. *Org. Lett.* **2005**, *7*, 3339. (e) Harada, Y.; Nakanishi, J.; Fujihara, H.; Tobisu, M.; Fukumoto, Y.; Chatani, N. *J. Am. Chem. Soc.* **2007**, *129*, 5766. (f) Zhao, P.; Liu, Y.; Xi, C. *Org. Lett.* **2015**, *17*, 4388.
(11) (a) Vasilyev, A. V.; Walspurger, S.; Haouas, M.; Sommer, J.; Pale, P.; Rudenko, A. P. *Org. Biomol. Chem.* **2004**, *2*, 3483. (b) Vasilyev, A. V.; Walspurger, S.; Pale, P.; Sommer, J. *Tetrahedron Lett.* **2004**, *45*, 3379. (c) Vasil'ev, A. V.; Walspurger, S.; Pale, P.; Sommer, J.; Haouas, M.; Rudenko, A. P. *Russ. J. Org. Chem.* **2004**, *40*, 1769.
(12) (a) Zhou, J.; Zhang, G. − L.; Zou, J. − P.; Zhang, W. *Eur. J. Org. Chem.* **2011**, *2011*, 3412. (b) Pan, C.; Huang, B.; Hu, W.; Feng, X.; Yu, J.-T. *J. Org. Chem.* **2016**, *81*, 2087.
(13) (a) Hu, B.-L.; Pi, S.-S.; Qian, P.-C.; Li, J.-H.; Zhang, X.-G. *J. Org. Chem.* **2013**, *78*, 1300. (b) Du, H.-A.; Tang, R.-Y.; Deng, C.-L.; Liu, Y.; Li, J.-H.; Zhang, X.-G. *Adv. Synth. Catal.* **2011**, *353*, 2739. (c) Du, H.-A.; Zhang, X.-G.; Tang, R.-Y.; Li, J.-H. *J. Org. Chem.* **2009**, *74*, 7844. (d) Yang, Z.-J.; Hu, B.-L.; Deng, C.-L.; Zhang, X.-G. *Adv. Synth. Catal.* **2014**, *356*, 1962.
(14) (a) Koeller, K. M.; Wong, C.-H. *Chem. Rev.* **2000**, *100*, 4465. (b) Climent, M. J.; Corma, A.; Iborra, S. *Chem. Rev.* **2011**, *111*, 1072.
(15) Yan, W.; Wang, Q.; Chen, Y.; Petersen, J. L.; Shi, X. *Org. Lett.* **2010**, *12*, 3308.
(16) Zhu, Y.; Sun, L.; Lu, P.; Wang, Y. *ACS Catal.* **2014**, *4*, 1911.
(17) Liu, J.; Fan, C.; Yin, H.; Qin, C.; Zhang, G.; Zhang, X.; Yi, H.; Lei, A. *Chem. Commun.* **2014**, *50*, 2145.

DOI: 10.1021/acs.joc.6b00762
J. Org. Chem. 2016, 81, 5710−5716