Regioselective Carbonylative Heteroannulation of *o*-Iodothiophenols with Allenes and Carbon Monoxide Catalyzed by a Palladium Complex: A Novel and Efficient Access to Thiochroman-4-one Derivatives

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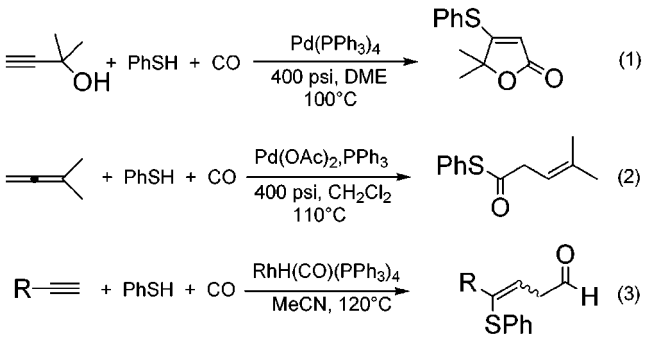
The palladium-catalyzed carbonylative ring-forming reactions of 2-iodothiophenol, and the corresponding substituted derivatives, with allenes and carbon monoxide are described. The reactions afford thiochroman-4-ones in good to excellent isolated yields with quite high regioselectivity. The catalytic heteroannulation may involve regioselective addition of the sulfur moiety of the reactants on the more positive end of the allene, arylpalladium formation, CO insertion, subsequent intramolecular cyclization, and then reductive elimination. The regioselectivity is probably governed by electronic effects.

Introduction

Transition metal-catalyzed carbo- and heteroannulations are now emerging as a unique, powerful, and versatile synthetic approach toward a variety of structural cores of complex organocarbo- and heterocycles.[1] Examples include the palladium-catalyzed intra- and intermolecular cyclization of unsaturated substrates such as alkynes,[2] 1,2-[3] and 1,3-dienes,[4] vinyl cyclopropanes and cyclobutanes,[5] homoallylic alcohols,[6] and imines[7] with functionally substituted aromatic or vinyl[3a,8] iodides or bromides, affording the corresponding benzo[*b*]furans, indoles, spiroisoindolinones, and other heterocycles. In contrast, much less information is available on the cyclocarbonylation version of such processes,[3b,9] although in principle, acylmetal derivatives can add to π-bonds via carbometalation.[10] As part of our continuing studies on the scope of palladium-catalyzed carbonylation methodology, we would like to explore such synthetic methods employing carbon monoxide as a direct C-1 resource and involving insertion of carbon−carbon multiple bonds to acylpalladation derivatives. Furthermore, in sharp contrast with the palladium-catalyzed cyclization of *o*-iodophenols and anilines with unsaturated substrates, application of these methodologies in which *o*-iodothiophenol is employed as a reagent instead of its oxo and nitro analogues seems to be unexplored. A possible reason for this is the acceptance that sulfur-containing compounds can act as poisons for noble metals.[11] However, we and others have recently demonstrated that thiols are compatible with palladium, in Pd(0)-catalyzed thiolactonization[12] (eq 1) and thiocarbonylation[13](eq 2), as well as with rhodium, in Rh(I)-catalyzed thioformylation (eq 3).[14]



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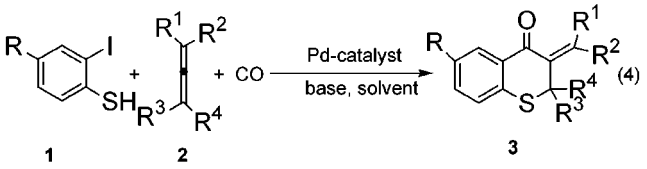
Accordingly, we envisioned that the carbonylative heteroannulation of *o*-iodothiophenols with allenes and carbon monoxide could be carried out, affording the corresponding thiochroman-4-one derivatives (eq 4).



R=H, Me, Cl.
R^1, R^2, R^3, and R^4=H, alkyl, -CO_2Et, or cycloalkyl

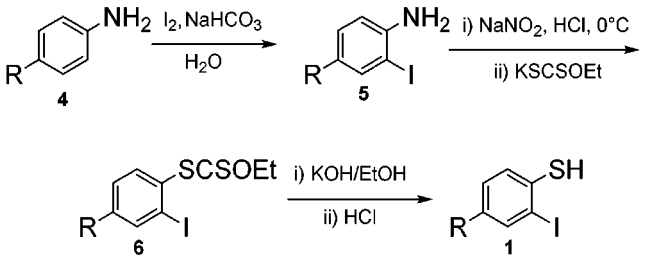
Of particular interest is the fact that some 4-thiochromanone derivatives are potent antifungal agents[15] and very useful precursors[16,17]of other heterocyclic compounds. Of the various routes to their preparation,[18] the methodology presented herein is one of the most straightforward and efficient ways to afford such compounds.

Results and Discussion

The starting materials were prepared by standard methodology.[19,20] For example, *o*-iodothiophenols (**1a**−**c**) were prepared by the reactions shown in Scheme 1.

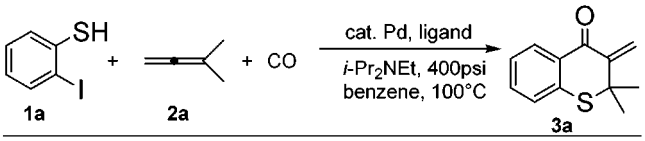
Initial studies were focused on examining the feasibility of the carbonylation annulation and optimizing reaction conditions that could be applied to a variety of allenes and *o*-iodothiophenol derivatives. The reaction of 2-iodothiophenol (**1a**) and 3-methyl-1, 2-butadiene (**2a**) with carbon monoxide was chosen as a model reaction. The optimal reaction conditions used previously for the palladium-catalyzed carbonylation of *o*-iodophenols with allenes[3b] were initially employed in the present case. This reaction was run on a 1 mmol scale, using 5 mol % Pd(OAc)$_2$ as catalyst, 5 mol % dppb as ligand, 3 equiv of allene, and 1.5 equiv of *N*-ethyldiisopropylamine in 5 mL of benzene, at 100 °C, under a pressure of 400 psi carbon monoxide for 24 h and gave **3a** in 74% isolated yield (eq 5). The effects of varying the catalyst, ligand, solvent, base, and reaction temperature on the model reaction were then examined.

Scheme 1



1a: R=H
1b: R=Me
1c: R=Cl

Table 1. Optimization of Catalysts and Ligands[a]



entry	catalyst	ligand	time (h)	yield[b] (%)
1	$Pd(OAc)_2$	dppb	24	74
2	$Pd(OAc)_2$	dppp	24	58
3	$Pd(OAc)_2$	dppe	48	7[c]
4	$Pd(OAc)_2$	dppf	24	87
5	$Pd(OAc)_2$	PPh_3	24	70
6	$Pd(OAc)_2$	PCy_3	24	45
7	$PdCl_2$	dppf	48	77
8	$Pd_2(dba)_3$	dppf	60	80
9	$Pd_2(dba)_3$·$CHCl_3$	dppb	60	64
10	$Pd_2(dba)_3$·$CHCl_3$	dppf	60	84
11	$Pd(PPh_3)_4$	dppf	60	76

[a] Reaction conditions: 2-iodothiophenol (1 mmol), 3-methyl-1, 2-butadiene (5 mmol), catalyst (0.05 mmol), PPh_3 or PCy_3 (0.1 mmol, if used), dppb, dppp, dppe, or dppf (0.05 mmol, if used), *i*-Pr_2NEt (1.5 mmol), 400 psi, 100°C, benzene (5 mL). [b] Isolated yield. [c] 38% of **1a** was recovered.

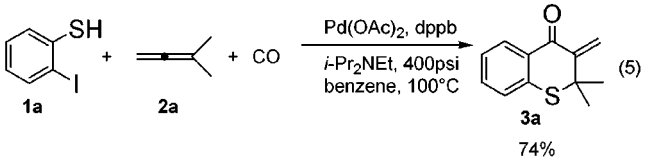


Table 1 shows the results of the reaction using several palladium catalysts and mono- and bis-phosphine ligands. These results show that both palladium(0) and palladium(II) complexes were excellent catalysts for the carbonylative heteroannulation, although palladium(0) complexes catalyzed this reaction at a slower rate. The ligands employed played an important role in this transformation, with 1,1′-bis(diphenylphosphino)ferrocene (dppf) being an excellent ligand for both palladium(0) and palladium(II) catalysts (Table 1, entries 4 and 7−11). In particular, the use of $Pd(OAc)_2$ with 1 equiv of dppf was the most effective catalyst system for the formation of **3a** in 87% yield (Table 1, entry 4). Although 1,3-bis(diphenylphosphino)propane (dppp) and 1, 4-bis(diphenylphosphino)butane (dppb) were also effective as added ligands for this palladium-catalyzed reaction, the results were generally inferior to those of dppf (Table 1, entries 1, 2, and 9). Compared to other bidentate phosphines, 1,2-bis(diphenylphosphino)ethane (dppe) is almost ineffective (Table 1, entry 3). This may be due to

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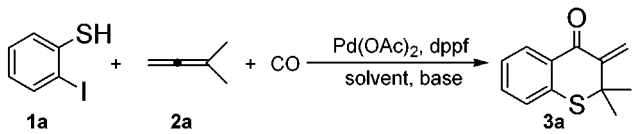
Table 2. Optimization of Solvents, Bases, and Reaction Temperature[a]



1a 2a 3a

entry	solvent	base	*T* (°C)	time (h)	yield[b] (%)
1	benzene	*i*-Pr_2NEt	100	24	87
2	DMF	*i*-Pr_2NEt	100	24	58
3	THF	*i*-Pr_2NEt	100	24	52
4	DMSO	*i*-Pr_2NEt	100	24	33
5	CH_3CN	*i*-Pr_2NEt	100	24	66
6	toluene	*i*-Pr_2NEt	100	24	78
7	benzene	KOAc	100	60	24
8	benzene	K_2CO_3	100	60	29
9	benzene	Et_3N	100	24	64
10	benzene	DBU[c]	100	24	34
11	benzene	DABCO[d]	100	24	37
12[e]	DMF	K_2CO_3	100	48	69
13	DMF	KOAc	100	48	63
14	benzene	*i*-Pr_2NEt	70	36	0[f]
15	benzene	*i*-Pr_2NEt	130	24	70
16	benzene	*i*-Pr_2NEt	150	24	44

[a] Reaction conditions: 2-iodothiophenol (1 mmol), 3-methyl-1, 2-butadiene (5 mmol), $Pd(OAc)_2$ (0.05 mmol), dppf (0.05 mmol), *i*-Pr_2Et, Et_3N, DBU, or DABCO (1.5 mmol, if used), K_2CO_3 or KOAc (3 mmol, if used), solvent (5 mL), 400 psi. [b] Isolated yield. [c] 1,8-Diazabicyclo[5.4.0]under-7-ene. [d] 1,4-Diazabicyclo[2.2.2]octane.[e] Using a 9:1 DMF/water mixture afforded **3a** in 18% yield, plus many other products. An inseparable mixture of numerous products resulted using water as the solvent. [f] The decarbonylation product, *o*-iodophenyl 3-methyl-2-butenyl sulfide, was obtained in 74% yield.

the fact that the rate of carbon monoxide insertion into a Pd−C bond is faster for those alkylpalladium bisphosphine complexes that contain a more flexible metal ligand chelate ring.[21] The monodentate ligands, like PPh_3 and PCy_3, can be used for this reaction, but they are not as effective as dppf (Table 1, entries 5 and 6). Therefore, it was decided to use $Pd(OAc)_2$ with dppf as the catalyst system and examine the effect of different solvents, bases, and reaction temperature on the carbonylative heteroannulation.

It can be concluded from the results summarized in Table 2 that the reaction is significantly influenced by the solvent and base employed. For example, when *N*-ethyldiisopropylamine is used as a base, the reaction works very well in benzene and gives the product **3a** in 87% isolated yield (Table 2, entry 1); however, under the same conditions, using DMF as a solvent, the yield of **3a** decreased to 58% (Table 2, entry 2). This was of interest, as previous studies noted that DMF was the solvent of choice.[22] Other solvents, such as THF, DMSO, CH_3CN, and toluene, can be employed as the solvent for the reaction, but none appears to be as effective as benzene (compare entries 1−6 in Table 2).

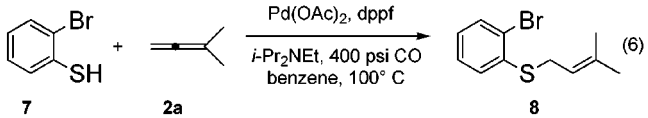
In addition to *N*-ethyldiisopropylamine, we have examined a variety of other bases, including inorganic and organic ones, for the reaction (Table 2, entries 7−13). These results show that solvents and bases are interdependent. For example, when benzene was employed as the solvent, *N*-ethyldiisopropylamine and triethylamine were observed to be very effective for the reaction. However, the use of K_2CO_3, KOAc, DBU, and DABCO resulted in decreased yields (Table 2, entries 7−11). It is worth noting that in DMF, K_2CO_3 is a better base for the model reaction than *i*-Pr_2NEt (Table 2, entries 2 and 12), while both benzene/Et_3N and DMF/KOAc systems are similarly effective for this carbonylative heteroannulation (Table 2, entries 9 and 13). DBU and DABCO, which were used in the palladium-catalyzed carbonylative coupling of 2-hydroxylaryl iodides with ethynylarenes[22b] and annulation of iodoanilines and ketones,[23] respectively, did not work well in the present reaction (Table 2, entries 10 and 11).

The reaction temperature is another critical factor for the successful carbonylative heteroannulation, with the best result being attained at 100 °C. Variations of the temperature from this value have been shown to be detrimental to the reaction. For instance, increasing the temperature to 150 °C gave only 44% yield (Table 2, entry 16), while decreasing the temperature to 70 °C gave exclusively the decarbonylation product in 74% yield (Table 2, entry 14).

We did not rigorously examine the effect of CO pressure on the reaction; however, we found that no carbonylation product was formed when the pressure of CO was lower than 100 psi, and when the pressure was raised beyond 1000 psi, a complicated mixture was obtained. In subsequent studies, 400 psi of carbon monoxide was usually used, consistent with our previous experience with other carbonylation reactions.[3b,13]

The heteroannulation of allenes is also sensitive to the concentration of the allene. The reaction gave poor yields when only 1 equiv of the allene (relative to 2-iodothiophenol) was used, while 87% yield was attained when 3−5 equiv of allene was employed.

There has been much interest recently in intramolecular Heck-type coupling reactions[24] that employ aromatic chlorides[25] or bromides[26] as substrates. However, the carbonylative reaction of **2a** with commercially available 2-bromothiophenol (**7**) afforded the bromothioether (**8**) rather than thiochroman-4-one (**3a**) (eq 6). The difference in behavior may be a result of the lower rate of oxidative addition to an Ar−Br moiety, compared with Ar−I. Note that the iodo analogue of **8** was formed in 72% yield when **1a** was treated with **2a** and CO using 10% Pd/C as the catalyst.



7 2a 8

72%

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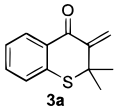
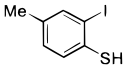
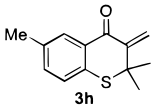
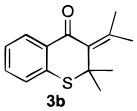
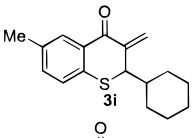
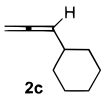
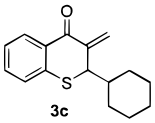
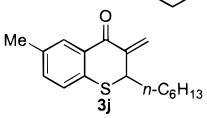
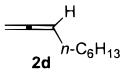
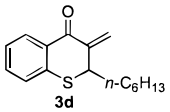
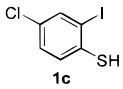
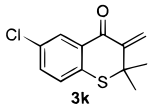
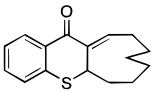
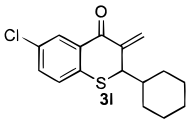
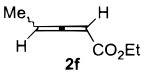
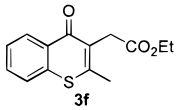
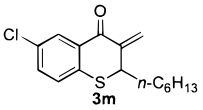
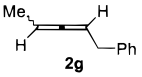
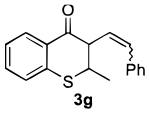
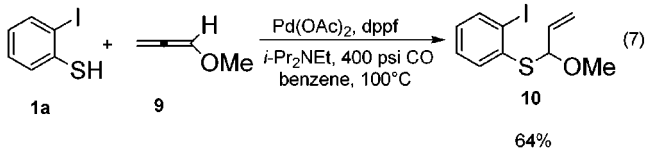
Table 3. Palladium-Catalyzed Carbonylative Heteroannulation of Allenes with *o*-Iodothiophenols and Carbon Monoxide (Eq 4)[a]

entry	iodothiophenol	allene	product	yield(%)[b]	entry	iodothiophenol	allene	product	yield(%)[b]
1	 **1a**	 **2a**	 **3a**	87	8	 **1b**	**2a**	 **3h**	92
2	**1a**	 **2b**	 **3b**	84	9	**1b**	**2c**	 **3i**	86
3[c]	**1a**	 **2c**	 **3c**	76	10	**1b**	**2d**	 **3j**	78
4	**1a**	 **2d**	 **3d**	68	11	 **1c**	**2a**	 **3k**	90
5	**1a**	 **2e**	 **3e**	72	12	**1c**	**2c**	 **3l**	77
6[d]	**1a**	 **2f**	 **3f**	72	13	**1c**	**2d**	 **3m**	74
7[e]	**1a**	 **2g**	 **3g**	90					

[a] Reaction conditions: *o*-iodothiophenol (1 mmol), allene (2−5 mmol), CO (400 psi), *i*-Pr_2NEt (1.5 mmol), $Pd(OAc)_2$ (0.05 mmol), dppf (0.05 mmol), benzene (5 mL), 100 °C. [b] Isolated yield. [c] Reaction time: 36 h. [d] Reaction time: 60 h. [e] The ratio of *E* to *Z* (*E*/*Z* = 1.5:1) was determined by ^{1}HNMR.

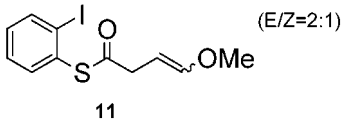
The above experiments indicated that the standard reaction conditions, with substitution of dppf for dppb, gave the best overall yield. Using these reaction conditions, the reactions of a variety of *o*-iodothiophenols and allenes were studied and the results are summarized in Table 3.

Acyclic, cyclic, terminal, and internal 1,2-dienes can be successfully employed in the reaction together with *o*-iodothiophenols containing electron-withdrawing or -donating groups (Table 3), to give the corresponding thiochromanone derivatives in good to excellent isolated yields. The regioselectivity of this carbonylative heteroannulation methodology is generally quite high. The terminal disubstituted allene, 3-methyl-1, 2-butadiene (**2a**), reacted with **1a**, **1b**, and **1c** to give only the *exo*-methylene products **3a**, **3h**, and **3k** with little variation in yields (Table 3, entries 1, 8, and 11). The reactions of monosubstituted allenes, like that of **2a**, are regioselective with nucleophilic attack of the −SH group occurring exclusively at the more substituted carbon of the allene unit (Table 3, entries 3 and 4). When the cyclic internal allene **2e** was employed, the expected product **3e** was obtained in 72% yield (Table 3, entry 5). When the unsymmetrical acyclic internal allene **2g** was employed as the substrate, thiochromanone **3g** was isolated in 90% yield as the sole product (Table 3, entry 7). The reaction is slower when the allene (**2f**) contains an electron-withdrawing group, but the reaction can proceed to completion by prolonging the reaction time to 60 h, affording the corresponding product **2f** in 72% yield (Table 3, entry 6). The more bulky allene, tetramethylallene (**2b**), has been successfully employed in this reaction without any problem, and to our knowledge, this is the first time that it has been used in this type of annulation process (Table 3, entry 2). Unlike palladium-catalyzed annulation of allene with functionalized vinylic halides,[3a] attempts to carry out the reaction of methoxyallene (**9**) with *o*-iodothiophenol and CO were unsuccessful (eq 7).

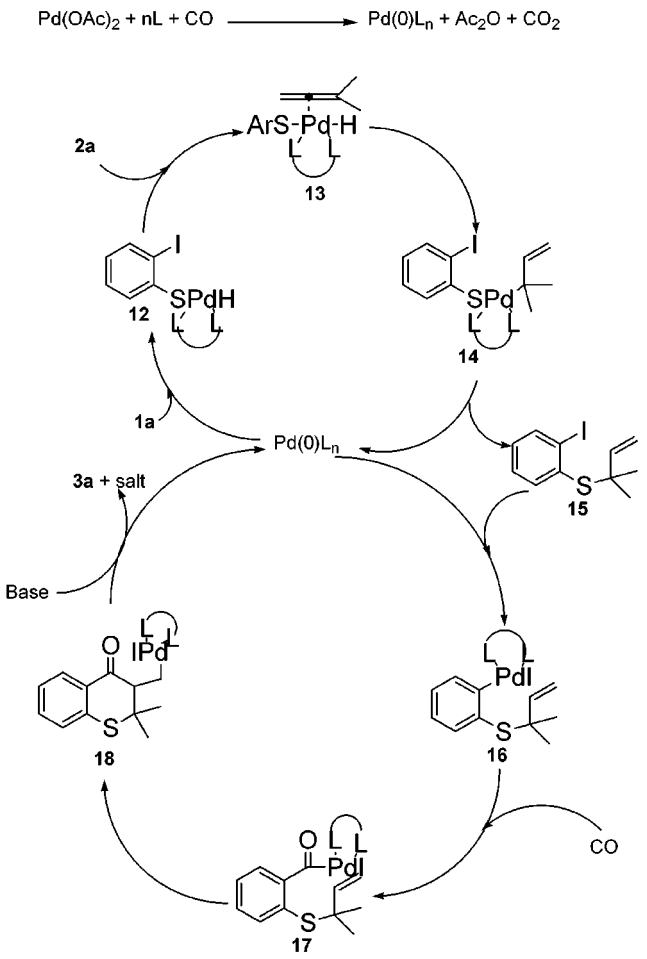


(7)

Such behavior was also observed for the palladium-catalyzed carbonylation[3b] of *o*-iodophenols with allenes. When the reaction was carried out with 2 equiv of dppf (relative to Pd catalyst) at 110 °C, the thiocarbonylation product **11** was isolated in 57% yield and no carbonylative heteroannulation product was obtained.



Scheme 2



Note that the regioselectivity of this reaction is consistent with palladium-catalyzed carboannulation of functionally substituted aryl halides with 1,2-dienes and its asymmetric as well as carbonylative versions[3b,f,g] and can be explained on the basis of electronic factors.[3b,f]

A probable mechanism for the carbonylative heteroannulation of 1,2-dienes with *o*-iodothiophenols is outlined in Scheme 2 (illustrated for **1a** and **2a**). It is conceivable that this reaction may proceed through initial palladium acetate reduction to palladium(0) in situ,[27] followed by oxidative addition of the *o*-iodothiophenol to palladium(0)[28] to form **12** and insertion of allene to **12** to produce a *σ*-allylpalladium intermediate **14 (**via **13)**. Reductive elimination of **14** would give the iodothioether (**15**). Oxidative addition of the latter to Pd(0) would generate complex **16**, which on subsequent CO insertion and intramolecular cyclization[9b,c] would afford **3a** and regenerate the catalyst.

Conclusion

In summary, this research has resulted in the regioselective carbonylative heteroannulation of 1,2-dienes with *o*-iodothiophenols and carbon monoxide catalyzed by palladium acetate and dppf to form thiochroman-4-one derivatives in good to excellent yields. To our knowledge, this is the first example of this type of annulation employing thiophenols as direct reactants. This one-pot procedure, the mild reaction conditions, and the easy access to the starting materials make this methodology of value to the area of thiochromanone chemistry.

Experimental Section

Allenes. 3-Methyl-1,2-butadiene (**2a**), tetramethylallene (**2b**), and cyclohexylallene (**2c**) are commercially available. Methoxyallene (**9**),[29] 1-phenyl-2,3-pentadiene (**2g**),[30] 1,2-cyclononadiene (**2e**),[31] 1,2-nonadiene (**2d**),[32] and ethyl 2,3-pentadienoate (**2f**)[33] were prepared according to the previously reported methods.

General Procedure for the Preparation of *o*-Iodoaniline 4b and 4c. Into a 100 mL beaker were placed 4-methylaniline (2.14 g, 0.02 mol) (for **4b**) or 4-chloroaniline (2.55 g, 0.02 mol) (for **4c**), $NaHCO_3$ (2.50 g, 0.03 mol), and water (20 mL). The mixture was cooled to 10−15 °C by the addition of a small amount of crushed ice. With stirring, powdered and resublimed iodine (5.08 g, 0.02 mol) was introduced in portions of 1 g at intervals of 3−5 min, after which time the color of the free iodine in the solution had practically disappeared and the reaction was complete. The organic phase was extracted from the reaction mixture with diethyl ether. The extracts were combined and dried with $MgSO_4$. Removal of the solvent and recrystallization of the crude product from *n*-hexane afforded **4b** and **4c** in 73 and 68% yields, respectively.

4-Methyl-2-iodoaniline (4b): needles; mp39−40 °C; IR (KBr) 3358, 3447 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 2.20 (s, 3H), 3.85 (br, s, 2H), 6.66 (d, 1H, J = 8.0 Hz), 6.95 (m, 1H), 7.45 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.80, 84.28, 114.63, 129.49, 130.00, 138.98, 114.25; MS (EI) *m*/*z* 233 (M^+); HRMS calcd for C_7H_8IN 232.9701, found 232.9686. Anal. Calcd for C_7H_8IN: C, 36.08; H, 3.46. Found: C, 36.16; H, 3.55.

General Procedure for the Preparation of *o*-Iodothiophenols 1a, 1b, and 1c. A solution of sodium nitrite (0.704 g, 0.01 mol) in water (2 mL) was added during 30 min to an ice -cooled solution of *o*-iodoaniline (0.01 mol) in 35% aqueous HCl (1.67 mL, 0.02 mol) containing ice (2.0 g), while potassium ethylxanthate was prepared by rapid stirring of a mixture of potassium hydroxide (0.796 g, 0.012 mol), ethanol (1.34 mL), water (2.5 mL), and carbon disulfide (1.332 g, 0.018 mol) for 2.5 h. The first solution of *o*-iodobenzenediazonium salt was added slowly to the prepared potassium ethylxanthate at 0−5 °C. After the addition, the mixture was heated at 50−55 °C for 0.5 h, cooled, and then extracted with ether. The organic phase was dried ($MgSO_4$) and evaporated to dryness in vacuo. The residue was refluxed with KOH (3.0 g, 0.046 mol) in absolute ethanol for 10 h, neutralized with 10% HCl, and extracted with ether. The combined organic phase was dried ($MgSO_4$) and evaporated to afford crude *o*-iodothiophenol, which was purified by chromatography using silica gel (eluant, hexane/ethyl acetate = 5:1). The isolated yields of **1a**, **1b**, and **1c** are 63, 54, and 66%, respectively.

2-Iodothiophenol (1a): oil; ^1H NMR (200 MHz, $CDCl_3$) δ 3.98 (s, 1H), 6.94−6.98 (m, 1H), 7.10−7.16 (m, 1H), 7.32 (d, 1H, J = 8.6 Hz), 7.50 (d, 1H, J = 8.6 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 121.98, 126.02, 127.84, 129.44, 133.07, 134.12; MS

(27) (a) Amatore, C.; Jutand, A.; M'Barki, M. *Organometallics* **1992**, *11*, 3009. (b) Amatore, C.; Carre, E.; Jutand, A.; M'Barki, M. *Organometallics* **1995**, *14*, 1818.

(28) Ogawa, A.; Ikeda, T.; Kimura, K.; Hirao, T. *J. Am. Chem. Soc.* **1999**, *121*, 5108.

(29) (a) Merz, A. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 846. (b) Meyer, A.; McCabe, D. J.; Curtis, M. D. *Organometallics* **1987**, *6*, 1491.

(30) Skattebol, L.; Solomon, S. *Organic Syntheses*; Wiley: New York, 1973; Collect. Vol. V, p 306.

(31) (a) Bach, R. D.; Mazur, U.; Brummel, R. N.; Lin, L.-H. *J. Am. Chem. Soc.* **1971**, *93*, 7120. (b) Okude, Y.; Hiyama, T.; Nozaki, L. *Tetrahedron Lett.* **1977**, *43*, 3829.

(32) Crabbe, P.; Nassim, B.; Robert-Lopes, M.-T. *Organic Syntheses*; Wiley: New York, 1990; Collect. Vol. VII, p 276.

(33) Lang, R. W.; Hansen, H.-J. *Organic Syntheses*; Wiley: New York, 1990; Collect. Vol. VII, p 232.

(EI) *m/z* 236.0 (M^+); HRMS calcd for C_5H_5IS 235.9157, found 235.9194.

Typical Procedure for the Palladium-Catalyzed Carbonylative Heteroannulation of Allenes with *o*-Iodothiophenols and Carbon Monoxide. A mixture of the allene (2−5 mmol), *o*-iodothiophenol (1 mmol), $Pd(OAc)_2$ (0.05 mmol), dppf (0.05 mmol), *i*-Pr_2NEt (1.5 mmol), and anhydrous benzene (5.0 mL) was heated to 100 °C with stirring, under an atmosphere of carbon monoxide (400 psi), in a stainless steel autoclave for 24−60 h. After the reaction, the autoclave was cooled to room temperature, excess carbon monoxide was released, and the crude reaction mixture was passed through a plug of Florisil, using hexane/ethyl acetate (1:1) as the eluant. The light yellow solution was evaporated to dryness and purified by column chromatography on silica gel using *n*-hexanes−ethyl acetate (95:5) as an eluant.

3-Methylene-2, 2-dimethyl-2, 3-dihydro-4*H*-1-benzothiopyran-4-one (3a): oil; IR (neat) 1670 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 1.60 (s, 6H), 5.46 (d, 1H, J = 0.69 Hz), 6.06 (d, 1H, J = 0.69 Hz), 7.18−7.19 (m, 2H), 7.22−7.39 (m, 1H), 8.15 (dd, 1H, J = 8 and 1.6 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 27.44, 46.73, 118.78, 125.37, 127.83, 129.69, 130.62, 133.52, 140.41, 150.56, 186.84; MS (EI) *m/z* 204.1 (M^+); HRMS calcd for $C_{12}H_{12}OS$ 204.0609, found 204.0598. Anal. Calcd for $C_{12}H_{12}OS$: C, 70.57; H, 5.93. Found: C, 70.62; H, 5.88.

3-(Dimethylmethylene)-2,2-dimethyl-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3b): oil; IR (neat) 1671 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 1.43 (s, 3H), 1.52 (s, 3H), 1.85 (s, 3H), 1.88 (s, 3H), 7.15−7.19 (m, 2H), 7.34−7.38 (m, 1H), 8.09−8.13 (m, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 23.10, 26.03, 29.82, 29.96, 48.84, 117.47, 124.68, 127.31, 127.43, 128.71, 135.05, 139.70, 141.02, 195.15; MS (EI) *m/z* 232.1 (M^+); HRMS calcd for $C_{14}H_{16}OS$ 232.0922, found 232.0916. Anal. Calcd for $C_{14}H_{16}OS$: C, 72.39; H, 6.95. Found: C, 72.44; H, 6.88.

2-Cyclohexyl-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3c): oil; IR (neat) 1670 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 0.88−1.16 (m, 4H), 1.54−1.74 (m, 6H), 2.16−2.24 (m, 1H), 3.46 (d, 1H, J = 7.4 Hz), 5.43 (s, 1H), 6.11 (s, 1H), 7.15−7.24 (m, 2H), 7.36−7.42 (m, 1H), 8.14 (d, 1H, J = 8.0 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 25.82, 26.60, 27.72, 28.40, 29.72, 32.31, 53.75, 115.55, 123.24, 125.24, 127.44, 128.02, 129.21, 132.96, 143.88, 185.88; MS (EI) *m/z* 258.1 (M^+); HRMS Calcd for $C_{16}H_{18}OS$ 258.1078, found 258.1075. Anal. Calcd for $C_{16}H_{18}OS$: C, 74.39; H, 7.03. Found: C, 74.46; H, 7.10.

2-*n*-Hexyl-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3d): oil; IR (neat) 1672 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 0.87 (t, 3H, J = 7.0 Hz), 1.13−1.70 (m, 10H), 3.50−3.54 (m, 1H), 5.49 (d, 1H, J = 0.8 Hz), 6.23 (d, 1H, J = 0.8 Hz), 6.92−7.04 (m, 2H), 7.33−7.50 (m, 1H), 7.86 (dd, 1H, J = 8.0, 1.8 Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ 14.07, 22.70, 24.50, 29.47, 31.70, 33.24, 47.76, 118.42, 120.53, 125.78, 127.66, 130.85, 135.40, 139.76, 141.92, 188.51; MS (EI) *m/z* 260 (M^+); HRMS calcd for $C_{16}H_{20}OS$ 260.1235, found 260.1241. Anal. Calcd for $C_{16}H_{20}OS$: C, 73.81; H, 7.75. Found: C, 73.88; H, 7.75.

2, 3-Dihydro-3′-cyclononena[2,3-*b*]-4*H*-1-benzothiopyran-4-one (3e): mp 57−58 °C; IR (KBr) 1672 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 1.31−1.60 (m, 4H), 2.05−2.42 (m, 8H), 3.95 (t, 1H, J = 7.4 Hz), 6.24 (t, 1H, J = 7.0 Hz), 7.14−7.36 (m, 4H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 24.04, 25.78, 26.93, 27.14, 30.88, 33.04, 58.04, 116.35, 126.34, 126.55, 130.08, 132.33, 135.76, 137.70, 142.36, 184.96; MS (EI) *m/z* 258.1 (M^+); HRMS calcd for $C_{16}H_{18}OS$ 258.1078, found 258.1080. Anal. Calcd for $C_{16}H_{18}OS$: C, 74.39; H, 7.03. Found: C, 74.46; H, 7.06.

2-Methyl-3-ethoxycarbonylmethyl-4*H*-1-benzothiopyran-4-one (3f): mp 71.5−72.0 °C; IR (KBr) 1673 cm^{-1} (PhCO−), 1738 cm^{-1} (−$CO_2C_2H_5$); ^1H NMR (200 MHz, $CDCl_3$) δ 1.24 (t, 3H, J = 7.4 Hz), 2.38 (s, 3H), 3.41 (s, 2H), 4.10 (q, 2H, J = 7.4 Hz), 7.18−7.20 (m, 2H), 7.22−7.40 (m, 1H), 8.09−8.15 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.12, 20.86, 31.02, 60.89, 114.76, 118.22, 123.30, 125.14, 135.06, 136.12, 153.64, 155.06, 170.78, 186.75; MS (EI) *m/z* 262 (M^+); HRMS Calcd for $C_{14}H_{14}O_3S$ 262.0664, found 262.0670. Anal. Calcd for $C_{14}H_{14}O_3S$: C, 64.11; H, 5.38. Found: C, 64.18, H, 5.44.

2-Methyl-3-(2-phenylvinyl)-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3g) (a mixture of stereoisomers): oil; IR (neat) 1668 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 1.46−1.53 (m, 3H), 3.24−3.36 (m, 1H), 3.74−3.78 (m, 1H), 6.05−6.22 (m, 1H), 6.52−6.70 (m, 1H), 6.95−7.08 (m, 2H), 7.20−7.52 (m, 6H), 7.85−7.92 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 17.72, 18.01, 47.36, 48.04, 56.38, 56.76, 116.88, 118.47, 119.50, 119.78, 121.04, 121.49, 126.73, 127.37, 127.62, 127.93, 128.50, 128.59, 128.74, 129.84, 135.90, 135.97, 135.63, 136.26, 136.37, 138.50, 147.62, 148.13, 189.72, 189.85; MS (EI) *m/z* 280.1 (M^+); HRMS calcd for $C_{18}H_{16}OS$ 280.0922, found 280.0926. Anal. Calcd for $C_{18}H_{16}OS$: C, 77.12; H, 5.76. Found: C, 77.16; H, 5.71.

3-Methyl-2,2,6-trimethyl-2, 3-dihydro-4*H*-1-benzothiopyran-4-one (3h): oil; IR (neat) 1666 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 1.60 (s, 6H), 2.34 (s, 3H), 5.45 (d, 1H, J = 0.8 Hz), 6.06 (d, 1H, J = 0.8 Hz), 7.13 (d, 1H, J = 8.0 Hz), 7.25 (d, 1H, J = 8.0 Hz), 7.97 (s, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 20.84, 27.43, 46.61, 118.64, 127.78, 129.86, 130.41, 134.67, 135.25, 136.99, 150.80, 187.03; MS (EI) *m/z* 218.1 (M^+); HRMS calcd for $C_{13}H_{14}OS$ 218.0765, found 218.0751. Anal. Calcd for $C_{13}H_{14}OS$: C, 71.53; H, 6.47. Found: C, 71.62; H, 6.45.

2-Cyclohexyl-6-methyl-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3i): oil; IR (neat) 1670 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 0.95−1.24 (m, 4H), 1.64−1.78 (m, 6H), 2.12−2.20 (m, 1H), 2.34 (s, 3H), 3.45 (d, 1H, J = 7.4 Hz), 5.42 (s, 1H), 6.10 (s, 1H), 7.18−7.25 (m, 2H), 7.95 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 20.84, 25.50, 25.85, 28.03, 31.22, 32.60, 39.39, 53.78, 123.11, 127.71, 128.07, 129.82, 130.47, 131.35, 134.70, 144.18, 186.12; MS (EI) *m/z* 272.1 (M^+); HRMS Calcd for $C_{17}H_{20}OS$ 272.1235, found 272.1229. Anal. Calcd for $C_{17}H_{20}OS$: C, 74.97; H, 7.41. Found: C, 74.88; H, 7.45.

2-*n*-Hexyl-6-methyl-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3j): oil; IR (neat) 1669 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 0.88 (t, 3H, J = 7.0 Hz), 1.20−1.88 (m, 10H), 2.36 (s, 3H), 3.88−3.92 (m, 1H), 5.52 (d, 1H, J = 1.0 Hz), 6.32 (d, 1H, J = 1.0 Hz), 7.33−7.40 (m, 2H), 7.77 (d, 1H, J = 0.6 Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ 14.07, 20.38, 23.52, 27.83, 28.90, 31.78, 33.40, 56.68, 119.04, 120.46, 122.05, 127.50, 128.33, 136.37, 139.63, 142.54, 187.60; MS (EI) *m/z* 274.1 (M^+); HRMS Calcd for $C_{17}H_{22}OS$ 274.1391, found 274.1393. Anal. Calcd for $C_{17}H_{22}OS$: C, 74.41; H, 8.09. Found: C, 74.43; H, 8.04.

6-Chloro-2,2-dimethyl-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3k): oil; IR (neat) 1674 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 1.59 (s, 6H), 5.49 (s, 1H), 6.09 (s, 1H), 7.14 (d, 1H, J = 8.4 Hz), 7.33 (dd, 1H, J = 8.4, 2.0 Hz), 8.10 (d, 1H, J = 2.0 Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ 27.33, 46.80, 119.64, 129.25, 131.51, 131.62, 133.41, 138.74, 149.73, 185.66; MS (EI) *m/z* 238.0 (M^+); HRMS calcd for $C_{12}H_{11}ClOS$ 238.0219, found 238.0200. Anal. Calcd for $C_{12}H_{11}ClOS$: C, 60.50; H, 4.66. Found: C, 60.58; H, 4.72.

6-Chloro-2-cyclohexyl-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3l): mp 76.5−77 °C; IR (KBr) 1674 cm^{-1} (C=O); ^1H NMR (200 MHZ, $CDCl_3$) δ 0.87−1.26 (m, 4H), 1.54−1.78 (m, 6H), 2.14−2.23 (m, 1H), 3.50 (d, 1H, J = 7.5 Hz), 5.43 (d, 1H, J = 0.8 Hz), 6.11 (d, 1H, J = 0.8 Hz), 7.20−7.27 (m, 1H), 7.80−7.84 (m, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 25.15, 25.23, 27.00, 31.88, 34.02, 39.64, 54.64, 119.84, 122.36, 129.68, 130.60, 133.13, 135.47, 138.37, 139.45, 190.02; MS (EI) *m/z* 292.1 (M^+); HRMS Calcd for $C_{16}H_{17}ClOS$ 292.0689, found 292.0688. Anal. Calcd for $C_{16}H_{17}ClOS$: C, 65.74; H, 5.87. Found: C, 65.78; H, 5.84.

6-Chloro-2-(*n*-hexyl)-3-methylene-2,3-dihydro-4*H*-1-benzothiopyran-4-one (3m): mp 61−62 °C; IR (KBr) 1673 cm^{-1} (C=O); ^1H NMR (200 MHz, $CDCl_3$) δ 0.86 (t, 3H, J = 7.0 Hz), 1.19−1.46 (m, 10H), 3.63−3.70 (m, 1H), 5.53 (d, 1H, J = 0.8 Hz), 6.32 (d, 1H, J = 0.8 Hz), 6.90 (d, 1H, J = 8.5 Hz), 7.24−7.36 (m, 1H), 7.64−7.83 (m, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ

14.07, 22.35, 27.59, 30.42, 31.63, 33.47, 57.35, 119.80, 123.63, 126.88, 133.13, 133.97, 138.42, 139.63, 142.07, 185.04; MS (EI) *m*/*z* 294.1 (M^+); HRMS calcd for $C_{16}H_{19}ClOS$ 294.0845, found 294.0851. Anal. Calcd for $C_{16}H_{19}ClOS$: C, 65.29; H, 6.51. Found: C, 65.24; H, 6.56.

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