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Iron(III)-Catalyzed Conia–Ene Cyclization of 2-Alkynic 1,3-Dicarbonyl Compounds

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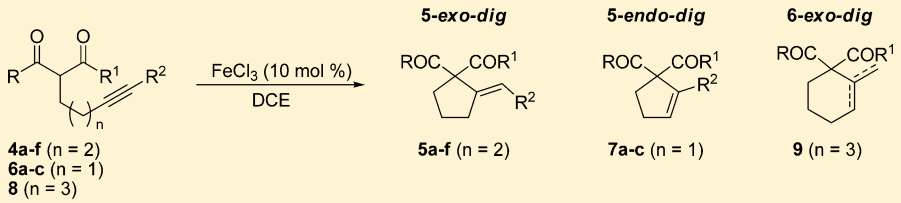
Supporting Information



ABSTRACT: A cheap, simple, and effective $FeCl_3$-catalyzed Conia–ene cyclization of 2-alkynic 1,3-dicarbonyl compounds was stereospecific to afford alkylidenecyclopentanes in (*E*)-isomers via the 5-*exo*-*dig* pathway. The 5-*endo*-*dig* and 6-*exo*-*dig* cyclizations were also possible, depending on the structure of the substrates.

INTRODUCTION

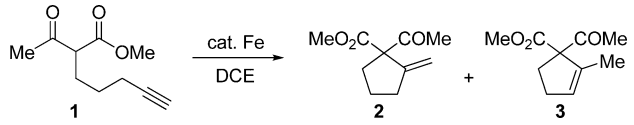
The growth of organic chemistry has been fueled by the increasing interest in researching the biological properties of natural products, thus leading to the constant development of new and novel synthetic methodologies. A motif common in natural products is 5-membered rings, which include cyclopentanes and heterocyclic rings such as furans, pyrroles, and indoles.[1]

Among various reactions to form cyclic structures, the Conia–ene reaction is a powerful method for forming cyclized compounds,[2] the intramolecular cyclization of acetylenic ketones and aldehydes. Various transition metals such as Au(I),[3] In(III),[4] Cu(I),[5] Ni(II),[6] Zr(II),[7] etc. have been extensively studied for such Conia–ene reactions.[8] Nevertheless, minimum studies were carried out using iron catalysts,[9] though it is noteworthy that iron salts are naturally abundant, cheap, and easy to handle with low toxicity. Thus, we have explored the catalytic ability of iron salts in the Conia–ene cyclizations.

RESULTS AND DISCUSSION

The Conia–ene cyclization was carried out using the ketoester **1** as the standard substrate to optimize the reaction conditions. As exemplified in Table 1, **1** underwent 5-*exo*-*dig* cyclization in the presence of various Fe catalysts. Most Fe catalysts employed required heating at 70 °C and produced only a moderate yield (47–72% yield) (entries 1–5), whereas $FeCl_3$ could catalyze the Conia–ene cyclization effectively at room temperature (entries 6–8 and 12). Fe_2O_3 was basically inert to such reactions (entry 4). In addition, it is noteworthy that $Fe(OTf)_3$ is much less efficient than $FeCl_3$ (entry 5). Varying the catalyst loading changed the results to some extent. As seen in entry 8, **1** readily cyclized to give methylenecyclopentane **2** in 72% yield, which isomerized partially to **3**. This isomerization could be easily avoided by decreasing the amount of $FeCl_3$ from 20 mol % (entry 8) to either 10 mol % (entry 6) or 5 mol % (entry 7), with which 10 mol % of $FeCl_3$ gave the best

Table 1. Optimizing Reaction Conditions for Conia–Ene Cyclization[a]



entry	Fe (mol %)	solvent	temp (°C)	time (h)	yield (%) 2	3
1	$FeBr_2$ (10)	DCE	70	5	65	
2	$FeCl_2$ (10)	DCE	70	6	72	
3	$Fe(acac)_3$ (10)	DCE	70	18	53	
4	Fe_2O_3 (10)	DCE	70	18		
5	$Fe(OTf)_3$ (10)	DCE	70	24	47	
6	$FeCl_3$ (10)	DCE	rt	1.5	76	
7	$FeCl_3$ (5)	DCE	rt	1.5	65	
8	$FeCl_3$ (20)	DCE	rt	1	54	18
9	$FeCl_3$ (20)	toluene	70	5	46	19
10	$FeCl_3$ (20)	CH_3NO_2	70	18	30	
11	$FeCl_3$ (20)	CH_3CN	70	18	50	
12	$FeCl_3$ (10) + Na_2CO_3 (1 equiv)	DCE	rt	2.5	63	

[a]Conditions: 1 (0.3 mmol) and Fe (5–20 mol %) in 2 mL of solvent at respective temperature.

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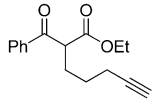
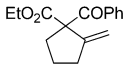
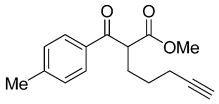
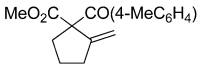
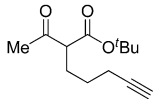
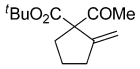
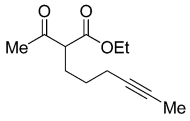
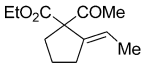
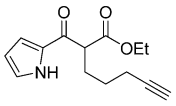
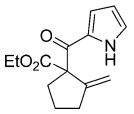
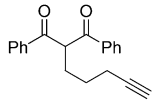
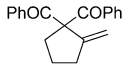
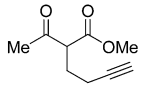
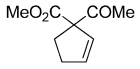
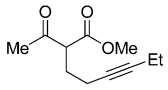
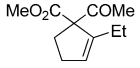
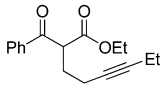
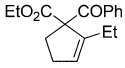
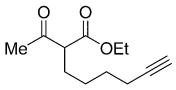
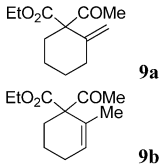
Table 2. Conia–Ene Cyclization of 4 or 6 Using $FeCl_3$ as Catalyst[a]

entry	substrate	time (h)	product	yield (%)
1	 **4a**	29	 **5a**	77
2[b]	 **4b**	26	 **5b**	73
3	 **4c**	14	 **5c**	70
4[c]	 **4d**	16	 **5d**	72
5[b]	 **4e**	23	 **5e**	73
6	 **4f**	58	 **5f**	58 (23)[d]
7[c]	 **6a**	48	 **7a**	51 (38)[d]
8	 **6b**	38	 **7b**	71
9	 **6c**	31	 **7c**	75
10[c]	 **8**	48	 **9a** **9b**	48[e] (41)[d]

[a]Conditions: **4**, **6**, or **8** (0.3 mmol) and $FeCl_3$ (10 mol %) in 2 mL of DCE at room temperature. [b]Reaction was carried out at 70 °C. [c]Reaction was carried out at 80 °C. [d]Recovery yield of the starting material. [e]**9a**:**9b** = 1:1.8.

result. When solvents such as nitromethane (entry 10) and acetonitrile (entry 11) were used, the reaction proceeded much less efficiently, even under prolonged heating at 70 °C. When the reaction was carried out in toluene (entry 9), **1** cyclized at 70 °C to give 65% yield after 5 h. However, the *exo*-methylenecyclopentane **2** again further isomerized to its thermodynamically more stable **3** to some extent. Addition of Na_2CO_3 did not facilitate the reaction at all (entry 12).

Table 2 summarizes the results of the Conia–ene cyclization achieved using 10 mol % of $FeCl_3$ in 1,2-dichloroethane. When the R group was changed from a methyl group to a phenyl group (**4a**), the reaction proceeded cleanly at room temperature to furnish the desired **5a** in 77%, but at an extended time of 29 h (entry 1). The introduction of an electron-donating methyl (**4b**) group at the *para* position of the phenyl R group decreased the reactivity of the Fe catalyst, thus requiring heating and a longer reaction time for the cyclization to afford **5b** in 73% yield (entry 2). Nonetheless, the addition of a bulky *tert*-butyl group at the R^1 position (**4c**) also cyclized smoothly to deliver the desired 5-membered olefin **5c** in 70% yield after

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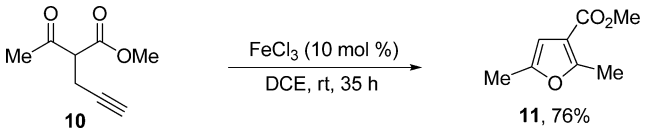
14 h (entry 3). Cyclization reaction also occurred smoothly with alkyl-substituted alkynes, yielding stereoselective (*E*)-**5d** isomer in 72% yield (entry 4). Substrate **4e** bearing a pyrrole moiety required heating at 70 °C for 23 h to afford **5e** in 73% yield (entry 5). This catalytic system can also be utilized in diketone derivative **4f**, but the cyclization was slower (entry 6).

We also explored the possibility of 5-*endo-dig* cyclization by reducing one carbon at the alkynyl chain (Table 2, entries 7–9). When **6a** was subjected to the standard conditions, the cyclization was very slow and required heating at 80 °C for a long period of time (48 h) to give the desired product in 51% yield together with the recovery of the starting material (38%) (entry 7). However, ethyl-substituted alkynes **6b** and **6c** were more reactive, and the alkynes proceeded at room temperature (entries 8 and 9). In the case where the alkynyl chain was extended by one more carbon, **8** underwent cyclization slowly to give **9a** via 6-*exo-dig*, which isomerized to a more stable **9b** (ratio of **9a**:**9b** = 1.0:1.8) (entry 10).

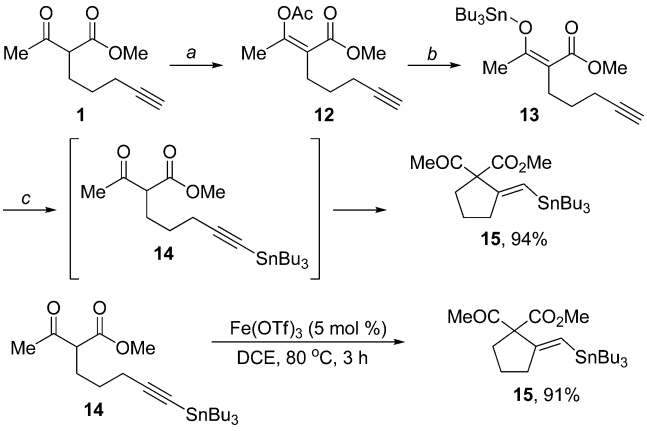
Alternatively, as illustrated in Scheme 1, when **10** was subjected to the standard cyclization conditions, trisubstituted furan ring **11** was isolated in 76% yield, which is in line with the previously reported result.[9f]

Scheme 1. Formation of Trisubstituted Furan 11 via $FeCl_3$ Catalysis of 10



Additional stannyl Conia–ene-type experiments were carried out using tin enolate **13** as shown in Scheme 2. The ketoester **1**

Scheme 2. Stannyl Conia–Ene-Type Cyclization[a]



[a]Ac_2O (1.2 equiv) and pyridine (1.5 equiv) in CH_2Cl_2.

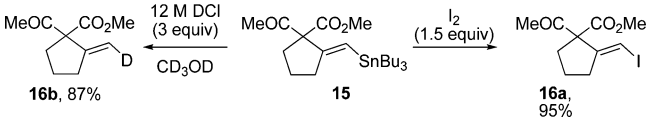
[b]Bu_3SnOMe (1.05 equiv) under neat conditions.

[c]$Fe(OTf)_3$ (5 mol %) in DCE.

was first treated with Ac_2O to give its acetate **12**, which was converted to **13** by stirring with Bu_3SnOMe under neat conditions. When the reaction mixture was subjected to the cyclization condition, the cyclized stannane product **15** was obtained exclusively as its (*E*)-isomer, however, in a low yield of only 23% when $FeCl_3$ was used. The yield was greatly improved to 94% when $Fe(OTf)_3$ was used instead, giving (*E*)-**15**. We then discovered that upon treatment with FeX_3 (X = Cl, OTf), intermediate **14** was formed at room temperature, which underwent cyclization at 80 °C. Intermediate **14** was successfully isolated, and treating it with $Fe(OTf)_3$ again eventually resulted in the same (*E*)-**15** in 91% yield.

In Scheme 3, (*E*)-**15** was readily converted to its iodide derivative **16a** and deuterated **16b**,[10] and subjected to the NOE

Scheme 3. Further Transformation of 15



experiment. Compounds **16a** and **16b** were also compared to similar previously known compounds[3a,5d,11] before the sterostructure was assigned.

Further studies on such stannyl Conia–ene experiments are represented in Table 3. The reactions for 5-*endo-dig* cyclization for synthesizing **18a–c** gave moderate yields of 63–66% (entries 1–3). In entry 4, a similar observation from Scheme 2 was seen when **19a** was cyclized to yield selectively bicyclic (*E*)-**20a**. By replacing the ester group with a sulfonyl group, **19b** not only underwent cyclization via the usual 5-*exo-dig* cyclization to yield (*E*)-**20b** but also via 6-*endo-dig* cyclization, whereby SO_2Ph was eliminated to give a more stable naphthalene derivative **20b′** (entry 5).

To confirm that the cyclization did not proceed via a radical intermediate (Scheme 4), substrate **1** was subjected to the standard cyclization conditions in the presence of a radical scavenger, TEMPO. However, the reaction did not proceed as expected. Nonetheless, this finding was not very conclusive, as previous reports have shown possible formation of metal complexes with TEMPO,[12] which would in turn mask the catalytic properties of Fe, thus inhibiting the reaction. When alkene **21** was treated with $FeCl_3$ overnight at 80 °C, no reaction was observed and the starting material was recovered unchanged. This result clearly indicates that the reaction was unlikely to go through a radical mechanism since alkyne and alkene are both susceptible toward radical attack.[13]

On the basis of experimental results obtained in this study, a plausible mechanism might involve an enol–alkyne iron complex, which undergoes a 5-*exo-dig* cyclization to yield stereospecific product in exclusive (*E*)-isomer after protonation of a vinyl iron intermediate (Scheme 5).

■ CONCLUSIONS

Iron(III) salts such as $FeCl_3$ and $Fe(OTf)_3$ were found to be very mild and effective catalysts in promoting the Conia–ene cyclizations in 5-*exo-dig*, 5-*endo-dig*, and 6-*exo-dig* manners, especially in the formation of 5-membered rings. With its naturally cheap and abundant properties, $FeCl_3$ will be a very useful catalytic source for such reactions. Synthetically useful vinylstannanes synthesized could be further utilized, especially in the application of coupling reactions.

■ EXPERIMENTAL SECTION

General Methods. A variety of chemical reagents were commercially purchased and used without further purification. Analytical TLC was carried out on precoated plates and visualized with UV light or stained with potassium permanganate. ^1H and ^{13}C NMR spectra were measured at 298 K on a 400 Fourier transform

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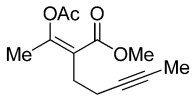
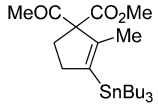
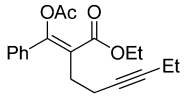
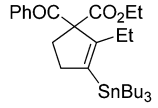
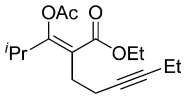
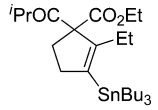
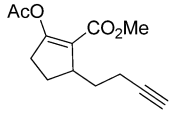
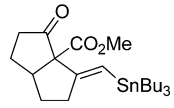
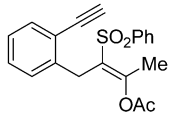
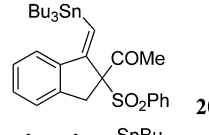
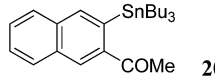
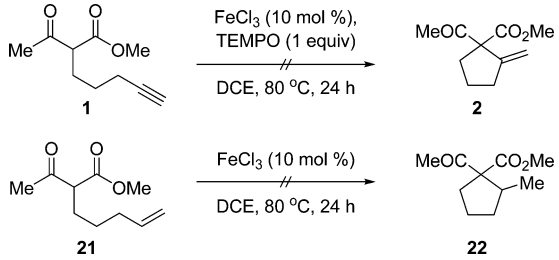
Table 3. Stanyl Conia–Ene Cyclization[a]

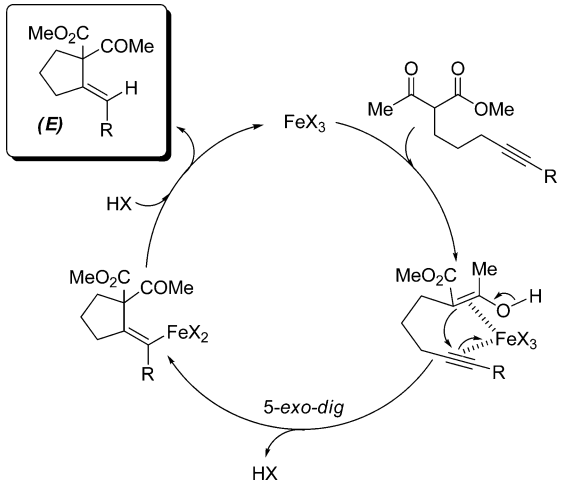
entry	substrate	time (h)	product	yield (%)
1	 **17a**	8	 **18a**	63
2	 **17b**	5.5	 **18b**	66
3	 **17c**	7	 **18c**	65
4	 **19a**	5	 **20a**	68
5	 **19b**	5	 **20b**  **20b'**	86[b]

[a]Conditions: **17** or **19** (0.3 mmol) and $Fe(OTf)_3$ (5 mol %) in 2 mL of DCE at 80 °C. [b]**20b**:**20b'** = 1.38:1.

Scheme 4. Exploring Possible Reaction Mechanism



Scheme 5. Proposed Reaction Mechanism



NMR spectrometer. Chemical shifts are reported in δ (ppm), relative to the internal standard of TMS. The signals observed were described as: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplets). The number of protons (n) for a given resonance is indicated as nH. Coupling constants are reported as J in Hz. ^{13}C NMR are reported as δ (ppm) in downfield from TMS and relative to the signal of chloroform-d (δ 77.00, triplet). Mass spectrometry was performed on a GC/HRMS spectrometer under electron impact (EI) ionization technique (mass analyzer: magnetic sector–electric sector). $FeCl_2$ (99.5%), $FeBr_2$ (98%), $Fe(acac)_2$ (99.9%), Fe_2O_3 (99.99%), $Fe(OTf)_3$ (90%), and $FeCl_3$ (98%), purchased from commercial suppliers, were used.

General Experimental Procedure for the Conia–Ene Cyclization. Anhydrous $FeCl_3$ (4.9 mg, 0.03 mmol, 10 mol % equiv) was carefully weighed and stirred in 1,2-dichloroethane (2 mL). 1,3-Dicarbonyl (0.3 mmol, 1.0 equiv) was then added, and the mixture was either stirred at room temperature or heated to the respective temperature. The residual crude product was concentrated in vacuo and purified by flash chromatography to afford the desired cyclized product.

Methyl 1-acetyl-2-methylenecyclopentanecarboxylate (2):[3a,5a] (Table 1, entry 6) 41.5 mg, 76% yield; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 5.30 (t, J = 2.1 Hz, 1H), 5.23 (t, J = 2.3 Hz, 1H), 3.75 (s, 3H), 2.48–2.38 (m, 3H), 2.25–2.16 (m, 4H), 1.76–1.62 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.6, 171.7, 148.7, 112.2, 70.42, 52.7, 35.0, 33.9, 26.6, 24.1.

Methyl 1-acetyl-2-methylcyclopent-2-enecarboxylate (3): (Table 1, entry 9) 10.4 mg, 19% yield; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 5.71 (d, J = 1.2 Hz, 1H), 3.76 (s, 3H), 2.69–2.61 (m, 1H), 2.61–2.32 (m, 2H), 2.29–2.19 (m, 1H), 2.18 (s, 3H), 1.82 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.1, 172.2, 137.4, 132.2, 74.7, 52.3, 32.8, 30.4, 26.6, 14.8; FTIR (NaCl, neat) ν 1703, 1647 cm^{-1}; HRMS (EI, $C_{10}H_{15}O_3$ (M + 1)) calcd 183.1021, found 183.1028.

Ethyl 1-benzoyl-2-methylenecyclopentanecarboxylate (5a):[3a,6] (Table 2, entry 1) 60.0 mg, 77% yield; yellow liquid; ^1H

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NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 7.4 Hz, 2H), 7.53 (t, J = 7.4 Hz, 1H), 7.42 (t, J = 7.4 Hz, 2H), 5.36 (t, J = 2.0 Hz, 1H), 5.22 (t, J = 2.1 Hz, 1H), 4.13 (m, 2H), 2.86 (dt, J = 13.2, 7.0 Hz, 1H), 2.52 (m, 2H), 2.19 (dt, J = 13.2, 7.0 Hz, 1H), 1.86 (m, 1H), 1.71 (m, 1H), 1.06 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 195.4, 171.8, 149.5, 135.4, 132.7, 128.8, 128.4, 111.8, 67.5, 61.6, 36.8, 34.4, 24.4, 13.7.

Methyl 1-(4-methylbenzoyl)-2-methylenecyclopentanecarboxylate (5b):[4d] (Table 2, entry 2) 57 mg, 73% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, J = 8.24 Hz, 2H), 7.22 (d, J = 8.14 Hz, 2H), 5.35 (t, J = 1.95 Hz, 1H), 5.18 (t, J = 2.16 Hz, 1H), 3.66 (s, 3H), 2.83 (td, J = 13.3, 6.77 Hz, 1H), 2.51 (m, 2H), 2.40 (s, 3H), 2.18 (td, J = 13.3, 6.90 Hz, 1H), 1.85 (m, 1H), 1.70 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 195.1, 172.9, 149.8, 143.9, 133.0, 129.6, 129.4, 112.3, 67.8, 53.1, 37.3, 34.7, 24.7, 22.0.

***tert*-Butyl 1-acetyl-2-methylenecyclopentanecarboxylate (5c):.**[3a,6] (Table 2, entry 3) 47.1 mg, 70% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.18 (t, J = 2.0 Hz, 1H), 5.13 (t, J = 2.19 Hz, 1H), 2.29 (m, 3H), 2.11 (s, 3H), 2.01 (m, 1H), 1.58 (m, 2H), 1.36 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.6, 170.1, 148.9, 111.6, 81.9, 71.1, 35.0, 34.1, 27.8, 26.8, 23.9.

(*E*)-Ethyl 1-acetyl-2-ethylidenecyclopentanecarboxylate (5d): (Table 2, entry 4) 45.4 mg, 72% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.70−5.61 (m, 1H), 4.20 (q, J = 7.1 Hz, 2H), 2.46−2.26 (m, 3H), 2.22−2.12 (m, 4H), 1.84−1.45 (m, 5H), 1.26 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.5, 171.6, 140.2, 122.2, 70.6, 61.3, 35.0, 29.5, 26.8, 23.7, 15.3, 14.0; FTIR (NaCl, neat): ν 1699, 1630 cm^{-1}; HRMS (EI, $C_{12}H_{19}O_3$ (M + 1)) calcd 211.1334, found 211.1348.

Ethyl 2-methylene-1-(1*H*-pyrrole-2-carbonyl)-cyclopentanecarboxylate (5e): (Table 2, entry 5) 54.1 mg, 73% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.48 (s, 1H), 6.99 (m, 1H), 6.75 (m, 1H), 6.25 (m, 1H), 5.36 (t, J = 2.0 Hz, 1H), 5.29 (t, J = 2.2 Hz, 1H), 4.17 (m, 2H), 2.76 (dt, J = 13.2, 6.6 Hz, 1H), 2.50 (m, 2H), 2.25 (m, 1H), 1.76 (m, 2H), 1.15 (t, J = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 186.7, 172.2, 148.9, 129.9, 124.4, 116.5, 112.8, 111.2, 67.4, 61.9, 38.1, 34.7, 24.7, 14.3; FTIR (NaCl, neat) ν 3292, 1733, 1641 cm^{-1}; HRMS (EI, $C_{14}H_{17}NO_3$ (M + 1)) calcd 247.1208, found 247.1206.

(2-Methylenecyclopentane-1,1-diyl)bis(phenylmethanone) (5f): (Table 2, entry 6) 50.5 mg, 58% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81 (app d, J = 8.0 Hz, 4H), 7.44 (tt, J = 7.43 Hz, 2H), 7.34 (app t, J = 7.45 Hz, 4H), 5.39 (t, J = 1.91 Hz, 1H), 4.96 (t, J = 2.0 Hz, 1H), 2.65 (m, 4H), 1.83 (m, 2H)); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.5, 150.8, 136.4, 133.1, 129.9, 128.8, 113.7, 74.0, 38.0, 35.2, 24.0.; FTIR (NaCl, neat) ν 1687, 1681 cm^{-1}; HRMS (EI, $C_{20}H_{18}O_2$ (M)) calcd 290.1307, found 290.1305.

Methyl 1-acetylcyclopent-2-enecarboxylate (7a):[14] (Table 2, entry 7) 25.7 mg, 51% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.08−6.00 (m, 1H), 5.92−5.82 (m, 1H), 3.74 (s, 3H), 2.55−2.33 (m, 4H), 2.18 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 203.9, 172.3, 136.4, 128.6, 73.5, 52.6, 31.9, 30.1, 26.4.

Methyl 1-acetyl-2-ethylcyclopent-2-enecarboxylate (7b):[3b] (Table 2, entry 8) 41.8 mg, 71% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74 (m, 1H), 3.75 (s, 3H), 2.62 (m, 1H), 2.41 (m, 2H), 2.22 (m, 1H), 2.17 (s, 3H), 2.13 (m, 2H), 1.10 (t, J = 7.36 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.4, 172.5, 143.9, 129.4, 74.9, 52.3, 32.9, 30.5, 26.7, 21.7, 12.4.

Ethyl 1-benzoyl-2-ethylcyclopent-2-enecarboxylate (7c): (Table 2, entry 9) 61.3 mg, 75% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (app d, J = 7.07 Hz, 2H), 7.52 (tt, J = 6.8, 1.9 Hz, 1H), 7.42 (app t, J = 6.8, 1.8 Hz, 2H), 5.78 (t, J = 2.05 Hz, 1H), 4.10 (q, J = 7.12 Hz, 2H), 3.09 (m, 1H), 2.55 (m, 1H), 2.40 (m, 1H), 2.29 (m, 2H), 2.01 (m, 1H), 1.14 (t, J = 7.38 Hz, 3H), 1.03 (t, J = 7.19 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.3, 172.5, 144.4, 135.7, 132.6, 128.8, 128.6, 128.4, 72.4, 34.0, 30.9, 21.7, 13.8, 12.5; FTIR (NaCl, neat) ν 1733, 1684 cm^{-1}; HRMS (EI, $C_{17}H_{20}O_3$ (M)) calcd 272.1412, found 272.1414.

Ethyl 1-acetyl-2-methylenecyclohexanecarboxylate (9a) and ethyl 1-acetyl-2-methylcyclohex-2-enecarboxylate (9b): (Table 2, entry 10) 30.3 mg, 48% combined yield, ratio of **9a**:**9b** = 1.0:1.8; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.77 (br s, 1.80H), 5.05 (s, 1H), 4.65 (s, 1H), 4.33−4.16 (m, 5.6H), 2.41−2.29 (m, 2.8H), 2.25 (s, 3H), 2.19 (s, 5.4H), 2.11−2.01 (m, 5.8H), 1.98−1.88 (m, 1.8H), 1.76 (dd, J = 3.4, 1.9 Hz, 5.4H), 1.62−1.52 (m, 8.4H), 1.33−1.25 (m, 8.4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 206.4 (**9b**), 205.4 (**9a**), 171.9 (**9a** and **9b**), 129.7 (**9a** and **9b**), 128.2 (**9b**), 112.0 (**9a** and **9b**), 65.4 (**9a** and **9b**), 61.4 (**9a**), 61.2 (**9b**), 34.6 (**9a**), 32.3 (**9a**), 29.9 (**9b**), 27.6 (**9a**), 27.3 (**9a**), 26.7 (**9b**), 25.1 (**9b**), 22.5 (**9a**), 21.7 (**9b**), 18.6 (**9b**), 14.1 (**9b**), 14.0 (**9a**); FTIR (NaCl, neat) ν 1699, 1641 cm^{-1}; HRMS (EI, $C_{12}H_{19}O_3$ (M + 1)) calcd 211.1334, found 211.1355.

Methyl 2,5-dimethylfuran-3-carboxylate (11):[15] (Scheme 1) 46.2 mg, 76% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.20 (s, 1H), 3.80 (s, 3H), 2.52 (s, 3H), 2.24 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.7, 157.7, 149.9, 113.7, 106.1, 51.1, 13.6, 13.2.

Methyl 2-(1-acetoxyethylidene)hept-6-ynoate (12): (Scheme 2) 91.9 mg, 82% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.76 (s, 3H), 2.35 (t, J = 7.8 Hz, 2H), 2.27 (s, 3H), 2.21 (s, 3H), 2.20−2.13 (m, 2H), 1.95 (t, J = 2.4 Hz, 1H), 1.81−1.51 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.2, 167.9, 157.3, 121.4, 84.3, 68.4, 51.7, 27.3, 26.2, 20.9, 19.4, 18.1; FTIR (NaCl, neat) ν 21156, 1759, 1717, 1647 cm^{-1}; HRMS (EI, $C_{12}H_{17}O_4$ (M + 1)) calcd 225.1127, found 225.1114.

Methyl 2-acetyl-7-(tributylstannyl)hept-6-ynoate (14): (Scheme 2) 97.6 mg, 69% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.74 (s, 3H), 3.47 (t, J = 7.4 Hz, 1H), 2.28 (dd, J = 9.5, 4.5 Hz, 2H), 2.24 (s, 3H), 1.98 (dd, J = 15.4, 7.8 Hz, 2H), 1.64−1.43 (m, 8H), 1.42−1.23 (m, 6H), 1.05−0.81 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.9, 170.1, 110.3, 82.5, 59.2, 52.3, 28.8, 28.7, 27.2, 26.9, 19.8, 13.6, 10.9; FTIR (NaCl, neat) ν 2999, 2955, 2930, 2879, 2118, 1715, 1647, 1435, 1246, 1057, 646 cm^{-1}; HRMS (EI, $C_{22}H_{41}O_3Sn$ (M + 1)) calcd 473.2078, found 473.2120.

(*E*)-Methyl 1-acetyl-2-((tributylstannyl)methylene)cyclopentanecarboxylate (15): (Scheme 2) 132.9 mg, 94% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.12 (dt, $^2J_{Sn-H}$ = 57.6, J = 2.0 Hz, 1H), 3.72 (s, 3H), 2.51−2.32 (m, 3H), 2.26 (dd, J = 13.2, 6.6 Hz, 1H), 2.21 (s, 3H), 1.82−1.68 (m, 2H), 1.58−1.39 (m, 6H), 1.38−1.24 (m, 6H), 1.06−0.75 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 204.3, 171.8, 156.6, 126.3, 72.7, 52.4, 35.8, 34.9, 29.1, 27.2, 26.6, 24.3, 13.7, 9.9; FTIR (NaCl, neat) ν 2957, 2926, 2872, 2853, 1710, 1638, 1458, 1233, 1072, 667 cm^{-1}; HRMS (EI, $C_{22}H_{41}O_3Sn$ (M + 1)) calcd 473.2078, found 473.2083.

(*E*)-Methyl 1-acetyl-2-(iodomethylene)cyclopentanecarboxylate (16a): (Scheme 3) 87.8 mg, 95% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.51 (t, J = 2.6 Hz, 1H), 3.77 (s, 3H), 2.62−2.50 (m, 1H), 2.50−2.39 (m, 2H), 2.32 (dt, J = 13.1, 6.6 Hz, 1H), 2.19 (s, 3H), 1.88−1.70 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.9, 170.2, 150.3, 78.2, 71.9, 53.0, 38.1, 36.3, 26.6, 22.9; FTIR (NaCl, neat): ν 1705, 1636 cm^{-1}; HRMS (ESI, $C_{10}H_{14}O_3I$ (M + 1)) calcd 308.9988, found 308.9993.

(*E*)-Methyl 1-acetyl-2-(deuteromethylene)cyclopentanecarboxylate (16b):[2] (Scheme 3) 47.8 mg, 87% yield, 84% deuterium incorporation; yellow liquid; 84% deuterium incorporation; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.30 (t, J = 2.1 Hz, 0.16H), 5.21 (t, J = 2.3 Hz, 1H), 3.75 (s, 3H), 2.53−2.35 (m, 3H), 2.25−2.13 (m, 4H), 1.83−1.65 (m, 2H).

Methyl 1-acetyl-2-methyl-3-(tributylstannyl)cyclopent-2-enecarboxylate (18a): (Table 3, entry 1) 88.9 mg, 63% yield; colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.74 (s, 3H), 2.53 (m, 3H), 2.23 (m, 1H), 2.15 (s, 3H), 1.85 (s, 3H), 1.48 (m, 6H), 1.32 (m, 6H), 0.95 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.9, 172.8, 146.5, 144.4, 77.2, 52.5, 38.7, 34.5, 29.6, 28.2, 27.7, 27.3, 26.9, 17.9, 17.2, 14.1, 14.0, 10.0; FTIR (NaCl, neat) ν 2955, 2925, 2871, 2851, 1741, 1717, 1462, 1249, 1072, 691 cm^{-1}; HRMS (FAB, $C_{22}H_{40}O_3NaSn$ (M^+ + Na)) calcd 495.1987, found 495.1989.

Ethyl 1-benzoyl-2-ethyl-3-(tributylstannyl)cyclopent-2-enecarboxylate (18b): (Table 3, entry 2) 111.2 mg, 66% yield; colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (app d, J = 7.08 Hz, 2H), 7.50 (tt, J = 7.44, J = 1.0 Hz, 1H), 7.41 (app t, J = 6.85 Hz, 2H), 4.10 (m, 2H), 3.03 (m, 1H), 2.61 (m, 1H), 2.42 (m, 1H), 2.29 (m, 3H),

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1.52 (m, 6H), 1.33 (m, 6H), 0.97 (m, 21H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 197.8, 151.4, 145.3, 136.4, 132.7, 129.0, 128.7, 74.1, 61.7, 38.9, 35.8, 29.6, 27.8, 24.7, 15.9, 14.1, 10.1; FTIR (NaCl, neat) ν 2956, 2927, 2871, 2853, 1734, 1684, 1447, 1254, 693 cm^{-1}; HRMS (EI, $C_{29}H_{46}O_3Sn$ (M)) calcd 562.2471, found 562.2469.

Ethyl 2-ethyl-1-isobutyryl-3-(tributylstannyl)cyclopent-2-enecarboxylate (18c): (Table 3, entry 3) 103.0 mg, 65% yield; colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.20 (m, 2H), 2.84 (m, 1H), 2.61 (m, 1H), 2.50 (m, 1H), 2.35 (m, 1H), 2.21 (m, 3H), 1.49 (m, 6H), 1.31 (m, 9H), 1.11 (d, J = 6.75 Hz, 3H), 1.09 (d, J = 6.8 Hz, 3H), 0.92 (m, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 212.7, 172.8, 151.6, 145.3, 76.7, 38.4, 38.1, 34.7, 29.7, 29.6, 29.5, 27.8, 27.7, 24.8, 21.0, 20.8, 15.9, 14.4, 14.1, 10.1; FTIR (NaCl, neat) ν 2957, 2927, 2871, 2853, 1740, 1712, 1462, 1238, 1070, 690 cm^{-1}; HRMS (EI, $C_{22}H_{39}O_3Sn$ (M − C_4H_9)) calcd 471.1921, found 471.1922.

(*E*)-Methyl 3-oxo-4-((tributylstannyl)methylene) octahydropentalene-3a-carboxylate (20a): (Table 3, entry 4) 98.6 mg, 65% yield; colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.29 (t, J = 29.0 Hz, 1H), 3.70 (s, 3H), 3.22 (m, 1H), 2.41 (m, 4H), 2.08 (m, 2H), 1.61 (m, 2H), 1.47 (m, 6H), 1.29 (m, 6H), 0.90 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.1, 170.2, 153.6, 126.6, 71.6, 52.6, 48.5, 37.9, 33.9, 29.4, 29.1, 27.2, 24.5, 13.7, 9.9; FTIR (NaCl, neat) ν 2954, 2927, 2870, 2853, 1737, 1705, 1452, 1246, 1066, 665 cm^{-1}; HRMS (EI, $C_{19}H_{31}O_3Sn$ (M − Bu)) calcd for $C_{19}H_{31}O_3Sn$ (M − Bu) 427.1295, found 427.1297.

(*E*)-1-(2-(Phenylsulfonyl)-1-((tributylstannyl)methylene)-2,3-dihydro-1*H*-inden-2-yl)ethanone (20b): (Table 3, entry 5) 90.2 mg, 50% yield; white solid; mp = 41−45 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92−7.84 (m, 2H), 7.51 (t, J = 7.5 Hz, 1H), 7.43−7.28 (m, 3H), 7.24−7.15 (m, 3H), 6.30 (d, $^2J_{Sn-H}$ = 31.6 Hz, 1H), 3.91 (d, J = 18.2 Hz, 1H), 3.68 (d, J = 18.2 Hz, 1H), 2.29 (s, 3H), 1.55−1.42 (m, 6H), 1.36−1.22 (m, 6H), 1.14−0.94 (m, 6H), 0.87 (t, J = 7.3 Hz, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.6, 150.1, 142.7, 140.1, 136.1, 133.6, 132.4, 131.4, 129.3, 127.9, 127.1, 125.0, 121.5, 86.9, 36.9, 29.1, 29.0, 28.9, 27.4, 27.2, 13.6, 10.8; FTIR (NaCl, neat) ν 2957, 2928, 2870, 2853, 1715, 1636, 1447, 1240, 1082, 687 cm^{-1}; HRMS (EI, $C_{30}H_{43}O_3SSn$ (M + 1)) calcd 603.1955, found 603.1943.

1-(3-(Tributylstannyl)naphthalen-2-yl)ethanone (20b′): (Table 3, entry 5) 49.6 mg, 36% yield; yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.40 (s, 1H), 8.17 (dd, $^2J_{Sn-H}$ = 48.0, J = 1.7 Hz, 1H), 7.97 (d, J = 7.8 Hz, 1H), 7.80 (d, J = 8.3 Hz, 1H), 7.61 (dd, J = 11.0, 4.1 Hz, 1H), 7.54 (dd, J = 8.6, 5.1 Hz, 1H), 2.73 (s, 3H), 1.59−1.51 (m, 6H), 1.33 (dt, J = 14.7, 7.4 Hz, 6H), 1.27−1.19 (m, 6H), 0.87 (t, J = 7.3 Hz, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.6, 144.2, 141.2, 133.4, 132.7, 130.8, 130.6, 130.0, 128.2, 126.2, 29.1, 27.3, 26.7, 13.6, 10.5; FTIR (NaCl, neat) ν 2957, 2928, 2870, 2855, 1638, 1449, 1271, 1072, 746 cm^{-1}; HRMS (EI, $C_{24}H_{37}OSn$ (M + 1)) calcd 461.1866, found 461.1880.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H and ^{13}C NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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