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Bi(OTf)$_3$-Catalyzed Tandem Meyer−Schuster Rearrangement and 1,4-Addition to the Resulting Vinyl Ketone

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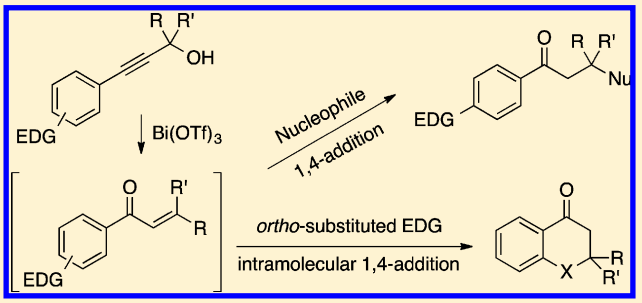
Supporting Information

ABSTRACT: Bi(OTf)$_3$-catalyzed Meyer−Schuster rearrangement of electron-rich propargyl alcohols, followed by 1,4-addition of the resulting vinyl ketone, proceeded smoothly though Meyer−Schuster rearrangement of primary propargyl alcohols is rare. This tandem reaction can be extended to an intramolecular version, featuring a one-pot dihydroquinolone synthesis.



Alkynes are among the most fundamental and important functional groups. Because of their useful reactivity, many investigations have focused on their synthetic applications.[1−4] We have recently been interested in the reaction of alkynes, especially electron-donating group (EDG) activated alkynes.[5] For example, an electron-rich alkyne is cleaved into two nitriles by treatment with *N*-iodosuccinimide and trimethylsilylazide under metal-free conditions.[5b] This reaction encouraged us to explore a new type of transformation of electron-rich alkynes. The Meyer−Schuster rearrangement[6] is the acid-catalyzed isomerization of secondary and tertiary propargyl alcohols to α,β-unsaturated ketones. Classical Meyer−Schuster rearrangement has been carried out in the presence of stoichiometric protonic acids. Catalytic methods have been reported recently,[7] but the examples with primary propargyl alcohols are particularly rare.[8] We envisioned that the Meyer−Schuster rearrangement of primary propargyl alcohols could provide highly reactive vinyl ketones, which might then be successively subjected to 1,4-addition. We report herein the tandem Meyer−Schuster rearrangement of primary propargyl alcohol/1,4-addition of nucleophile and its application for dihydroquinolone synthesis (Scheme 1).

First, we examined Meyer−Schuster rearrangement of electron-rich primary propargyl alcohol **1** as a substrate. Propargyl alcohol **1** was treated with 5 mol % of Lewis acid in 1,2-dichloroethane (DCE) in the presence of 3 equiv of EtOH as a nucleophile at 70 °C. A brief survey of several Lewis acids indicated that metal triflates showed catalytic activity for Meyer−Schuster rearrangement, and the results are listed in Table 1. Among these metal triflates, Bi(OTf)$_3$[9] showed the best catalytic activity, yielding the desired β-alkoxyketone **3** together with two byproducts, α,β-unsaturated ketone **2** and dimeric diketone **4** (vide infra) (entries 1−5). The formation of **4** was increased when the yield of **3** was lower (entry 3 vs 5). A decrease of EtOH reduced the yield of **3** (entry 6). Ten equivalents of EtOH greatly improved the yield to 94% (entry 7). Bismuth compounds are relatively low in toxicity in contrast to other Group 15 elements and the closely located heavy metals. Since bismuth(III) compounds exhibit Lewis acidity and are easy to handle and stable, the application of these compounds in organic synthesis has attracted recent attention.[10]

The plausible mechanism is shown in Scheme 2. α,β-Unsaturated ketone **2** was formed via Bi(OTf)$_3$-catalyzed Meyer−Schuster rearrangement of **1**, followed by 1,4-addition of EtOH, to give β-alkoxyketone **3**. Michael addition of allenol **5**, which was an intermediate of rearrangement, to **2** afforded dimeric diketone **4**. The structure of **4** was confirmed by X-ray crystallographic analysis.[11] To the best of our knowledge, this is the first Bi(OTf)$_3$-catalyzed Meyer−Schuster rearrangement.

Next, we examined the effect of substitution of the aromatic ring in **6**, which alters the electron density of the triple bond (Table 2). The reaction of an alkyne with a strong EDG on the aromatic ring proceeded smoothly to give β-alkoxyketone **7a** in good yield (entry 1). A moderate EDG showed low reactivity (entry 2). Substrates that did not have an EDG resulted in complex mixtures containing only trace amounts of product (entries 3 and 4). *meta*-Methoxyl-substituted **6e** did not proceed in the reaction, resulting in the recovery of starting material (entry 5). Decreasing the electron density of the alkynes decelerated the transformation, indicating that an EDG might facilitate the Meyer−Schuster rearrangement of primary propargyl alcohol rather than affect the 1,4-addition of EtOH.

The reactions of **1** with various alcohols as the nucleophile were examined (Table 3). Although water was not suitable for this reaction, other primary alcohols gave β-alkoxyketone **8** in good to excellent yields (entries 1−5). 2,2,2-Trifluoroethanol gave a poor yield because of low nucleophilicity (entry 6). When ethylene glycol was used, the Meyer−Schuster rearrange-

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Scheme 1. Tandem Meyer–Schuster Rearrangement/1,4-Addition to the Resulting Vinyl Ketone

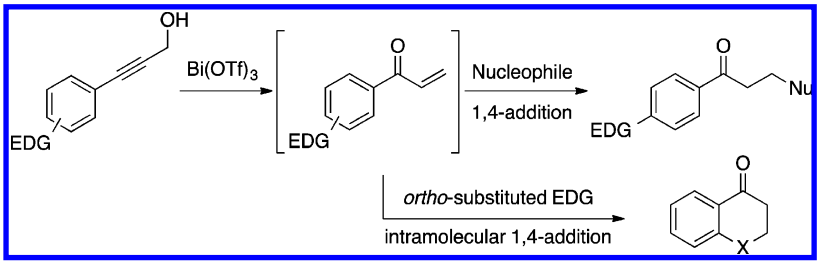
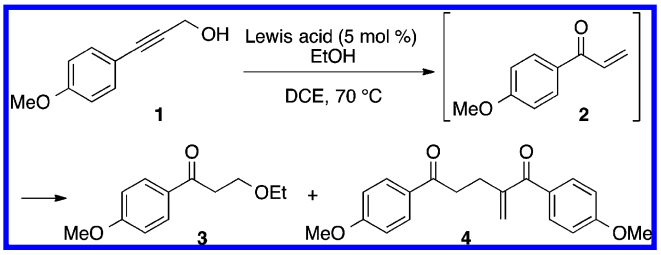


Table 1. Optimization of Reaction Conditions



entry	Lewis acid	EtOH (equiv)	time (h)	2 (%)	3 (%)	4 (%)
1	$Cu(OTf)_2$	3	2	6.6	69	5.9
2	$Al(OTf)_3$	3	2	10	65	11
3	$Sc(OTf)_3$	3	3	6.2	48	23
4	AgOTf	3	3	8.3	73	8.2
5	$Bi(OTf)_3$	3	1	6.4	77	6.8
6	$Bi(OTf)_3$	1.3	1	7.9	52	14
7	$Bi(OTf)_3$	10	3	2.0	94	1.8

Scheme 2. Plausible Reaction Mechanism

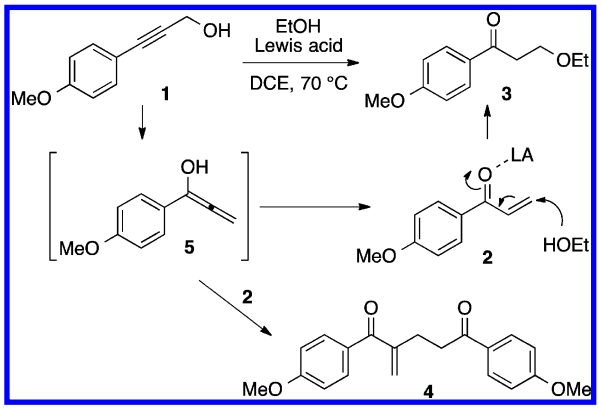
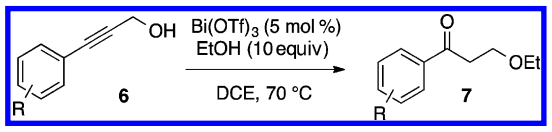


Table 2. Effect of Aromatic Substituent



entry	6	R	time	7	yield (%)
1	**6a**	*p*-$NHCO_2Et$	6 h	**7a**	91
2	**6b**	*p*-Me	2 days	**7b**	47
3	**6c**	*p*-H	3 days	**7c**	trace
4	**6d**	*p*-F	2 days	**7d**	trace
5	**6e**	*m*-OMe	2 days		recovery of sm

ment did not proceed (entry 7). Protected ethylene glycols afforded **3** in good to moderate yields (entries 8 and 9). A secondary alcohol could be used as the nucleophile (entry 10). As expected, bulky *t*-BuOH showed poor reactivity (entry 11). Using PhOH resulted in a complex mixture of products (entry 12).

This reaction was also carried out using secondary and tertiary propargyl alcohols (Table 4). Such substituted propargyl alcohols can undergo Meyer–Schuster rearrangement more easily, but 1,4-addition to the resulting *α,β*-unsaturated ketone is rather difficult. Secondary propargyl alcohol **9a** gave 63% of **10a** and 30% of **11a** regardless of reaction time (entries 1 and 2). The reactions of the more sterically hindered secondary propargyl alcohols afforded *α,β*-unsaturated ketone **11** as a major product (entries 3 and 4). Although the major product from tertiary propargyl alcohol **9d** was *α,β*-unsaturated ketone **11d** after 5 h, methyl ketone **12** and enyne **13** were formed as byproducts (entry 5). Enyne **13** could be a product of $Bi(OTf)_3$-catalyzed dehydration of **9d**, presumably by an E1 mechanism via a tertiary carbocation. Prolonging the reaction time to 10 h led to the increase of methyl ketone **12**, which was formed by addition of water to enone **11d**, followed by a retro-aldol reaction (entry 6). Tertiary propargyl alcohol **9e** only afforded *α,β*-unsaturated ketone **11e** in high yield (entry 7).

Finally, we applied this reaction to intramolecular cyclization, in which the nucleophilic moiety installed at the *ortho*-position of the benzene ring could add to the *α,β*-unsaturated ketone moiety to give a cyclic product (Table 5). Substrate **14a** had the methoxymethyl (MOM)-protected hydroxy substituent at the *ortho*-position, and MOM deprotection would be expected to occur under the reaction conditions. Intramolecular 1,4-addition of an oxygen atom of **15a** would be expected to give chroman-4-one **16a**. Unfortunately, this attempt failed to give any cyclized product regardless of addition of ethanol (entries 1–3).

Then, we tried tandem cyclization using substrate **14b**, which had the more nucleophilic carbamate substituent. When **14b** was treated with $Bi(OTf)_3$, dihydroquinolone **16b** was obtained together with *α,β*-unsaturated ketone **15b** (entry 4). Addition of EtOH improved the yield, and the best results were obtained with 5 equiv of ethanol (entries 5–7). Fortunately, in contrast to the results obtained from Table 4, secondary and tertiary propargyl alcohols **14c–f** could be employed for this reaction (entries 8–11), but **14g** afforded **16g** in low yield (entry 12)

In conclusion, we have demonstrated that electron-rich primary propargyl alcohols undergo $Bi(OTf)_3$-catalyzed Meyer–Schuster rearrangement and successive 1,4-addition of alcohol to give *β*-alkoxyketones. We were also able to extend this tandem reaction to an intramolecular version, featuring a one-pot dihydroquinolone synthesis.

EXPERIMENTAL SECTION

General. ^1H NMR and ^{13}C NMR spectra were recorded on a 600 MHz spectrometer. Chemical shifts were reported in *δ* (ppm) from tetramethylsilane as an internal standard. Data were reported as

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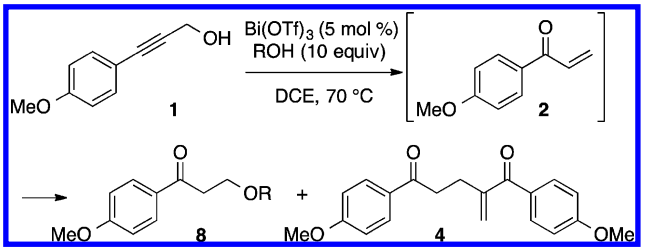
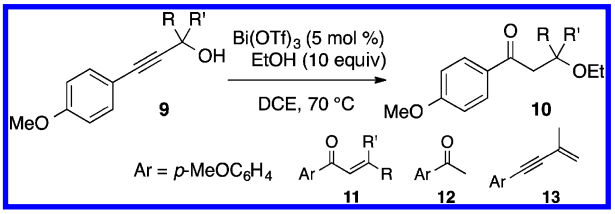
Table 3. Scope of the Alcohols



entry	ROH	time (h)	8	yield (%)	2 (%)	4 (%)
1	H_2O	2			26	22
2	MeOH	2	**8a**	94	0.9	0.9
3	$PhCH_2OH$[a]	1	**8b**	81		
4	allyl alcohol	1	**8c**	86		
5	propargyl alcohol	1	**8d**	55		12
6	CF_3CH_2OH	1	**8e**	5.2	23	23
7	ethylene glycol[a]	1 day			trace	trace
8	2-methoxyethanol[a]	2	**8f**	77	7.4	8.2
9	2-hydroxyethyl acetate[a]	2	**8g**	40	4.2	20
10	*i*-PrOH	6	**8h**	77	8.8	trace
11	*t*-BuOH	6	**8i**	27	26	trace
12	PhOH[a]	1				trace

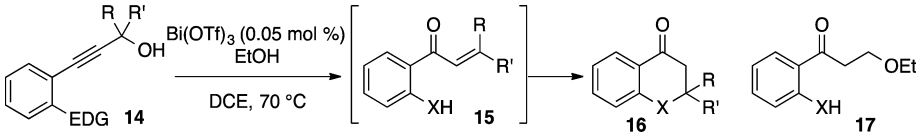
[a]5 equiv of ROH was used.

Table 4. Scope of the Substrates



entry	9	R	R′	time (h)	10	yield (%)	11	yield (%)	others
1	**9a**	Me	H	5	**10a**	63	**11a**	30	
2	**9a**	Me	H	10	**10a**	53	**11a**	32	
3	**9b**	*i*-Bu	H	6	**10b**	6.6	**11b**	70	
4	**9c**	Ph	H	6			**11c**	63	
5	**9d**	Me	Me	5			**11d**	73	**12** (2.5), **13** (18)
6	**9d**	Me	Me	10			**11d**	37	**12** (40)
7	**9e**	Ph	Ph	5			**11e**	94	

Table 5. Application in the Synthesis of Heterocyclic Compounds



entry	14	EDG	R	R′	EtOH (equiv)	time (h)	16	X	yield (%)	others
1	**14a**	OMOM	H	H		24	**16a**	O		
2	**14a**	OMOM	H	H	1.3	24	**16a**	O		**15a** (7.8), **17a** (13)
3	**14a**	OMOM	H	H	5	24	**16a**	O		**15a** (8.8), **17a** (36)
4	**14b**	$NHCO_2Et$	H	H		5	**16b**	NCO_2Et	28	**15b** (26)
5	**14b**	$NHCO_2Et$	H	H	1.3	5	**16b**	NCO_2Et	67	**15b** (7.3), **17b** (13)
6	**14b**	$NHCO_2Et$	H	H	5	24	**16b**	NCO_2Et	86	
7	**14b**	$NHCO_2Et$	H	H	10	48	**16b**	NCO_2Et	83	
8	**14c**	$NHCO_2Et$	Me	H	5	24	**16c**	NCO_2Et	87	
9	**14d**	$NHCO_2Et$	*i*-Bu	H	5	24	**16d**	NCO_2Et	84	
10	**14e**	$NHCO_2Et$	Ph	H	5	24	**16e**	NCO_2Et	79	
11	**14f**	$NHCO_2Et$	Me	Me	5	24	**16f**	NCO_2Et	80	
12	**14g**	$NHCO_2Et$	$-(CH_2)_5-$	$-(CH_2)_5-$	5	24	**16g**	NCO_2Et	30	

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follows: chemical shifts, relative integration value, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, br = broad, m = multiplet), coupling constants (Hz). Infrared spectra were obtained using an FT spectrometer. Analytical thin-layer chromatography was performed on Merck silica gel 60 F254 TLC plates.

General Procedure for the Preparation of Propargyl Alcohol. To a solution of aryl iodide (1 mmol) in Et_3N (5 mL) was added $Pd(OAc)_2$ (11.2 mg, 0.05 mmol), PPh_3 (26 mg, 0.1 mmol), CuI (9.5 mg, 0.05 mmol), and alkyne (1.3 mmol), and the mixture was stirred at room temperature under nitrogen. The reaction was monitored by TLC to establish completion. Saturated aqueous NH_4Cl solution was added to the reaction mixture and extracted with EtOAc (three times). The combined organic solution was washed with brine, dried over anhydrous $MgSO_4$, and concentrated at the reduced pressure. Column chromatography on silica gel using hexane/ethyl acetate as an eluent afforded propargyl alcohols (see the Supporting Information).

*Ethyl (4-(3-Hydroxyprop-1-yn-1-yl)phenyl)carbamate (**6a**).* Yield: 166.3 mg, 76%; yellow solid; mp 125−127 °C. ^{1}H NMR ($CDCl_3$) δ: 7.38−7.35 (4H, m), 6.64 (1H, br s), 4.49 (2H, s), 4.23 (2H, q, J = 7.2 Hz), 1.69 (1H, br s), 1.31 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 153.3, 138.2, 132.6, 118.1, 117.1, 86.5, 85.5, 61.5, 51.7, 14.5. IR ($CHCl_3$, cm^{-1}) 3608, 3434, 1734, 1609, 1581, 1521, 1506, 1411, 1379, 1313, 1237, 1197, 1065, 1023, 839. MS (EI): m/z = 219 (M^+). HRMS (EI): m/z calcd for $C_{12}H_{13}NO_3$: 219.0895; found: 219.0901.

*1-(4-Methoxyphenyl)-5-methylhex-1-yn-3-ol (**9b**).* Yield: 205.2 mg, 94%; brown oil. ^{1}H NMR ($CDCl_3$) δ: 7.36 (2H, d, J = 8.9 Hz), 6.83 (2H, d, J = 8.9 Hz), 4.63 (1H, q, J = 6.6 Hz), 3.81 (3H, s), 1.95−1.88 (1H, m), 1.80 (1H, d, J = 5.5 Hz), 1.75−1.70 (1H, m), 1.67−1.63 (1H, m), 0.98 (3H, d, J = 6.2 Hz), 0.97 (3H, d, J = 6.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 159.6, 133.1, 114.7, 113.9, 89.0, 84.6, 61.5, 55.2, 47.0, 24.8, 22.6, 22.5. IR ($CHCl_3$, cm^{-1}) 3601, 2961, 2936, 2225, 1608, 1510, 1467, 1442, 1387, 1290, 1249, 1237, 1174, 1107, 1174, 834, 810. MS (EI): m/z = 218 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{18}O_2$: 218.1307; found: 218.1302.

*Ethyl (2-(3-Hydroxybut-1-yn-1-yl)phenyl)carbamate (**14c**).* Yield: 212.3 mg, 91%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 8.13 (1H, br s), 7.36−7.31 (3H, m), 6.97 (1H, t, J = 7.6 Hz), 4.83 (1H, q, J = 6.8 Hz), 4.25 (2H, q, J = 7.2 Hz), 2.43 (1H, br s), 1.60 (3H, d, J = 6.8 Hz), 1.33 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 153.3, 139.1, 131.9, 129.8, 122.4, 117.7, 110.6, 98.0, 79.2, 61.4, 58.8, 24.4, 14.5. IR ($CHCl_3$, cm^{-1}) 3691, 3601, 3405, 2988, 2224, 2197, 1734, 1602, 1582, 1523, 1450, 1378, 1307, 1240, 1196, 1097, 1062, 933, 810. MS (EI): m/z = 233 (M^+). HRMS (EI): m/z calcd for $C_{13}H_{15}NO_3$: 233.1052; found: 233.1045.

*Ethyl (2-(3-Hydroxy-5-methylhex-1-yn-1-yl)phenyl)carbamate (**14d**).* Yield: 242.3 mg, 88%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 8.14 (1H, br s), 7.37 (1H, d, J = 8.2 Hz), 7.34−7.31 (2H, m), 6.98 (1H, t, J = 7.6 Hz), 4.72 (1H, q, J = 6.6 Hz), 4.25 (2H, q, J = 7.2 Hz), 1.95−1.93 (2H, m), 1.81−1.69 (2H, m), 1.33 (3H, t, J = 7.2 Hz), 1.01 (3H, d, J = 6.2 Hz), 0.99 (3H, d, J = 6.9 Hz). ^{13}C NMR ($CDCl_3$) δ: 153.3, 139.1, 131.8, 129.8, 122.4, 117.6, 110.7, 97.5, 80.0, 61.5, 61.4, 46.8, 25.0, 22.6, 22.5, 14.5. IR ($CHCl_3$, cm^{-1}) 3601, 3404, 2962, 1734, 1582, 1521, 1451, 1388, 1307, 1240, 1063, 1042. MS (EI): m/z = 275 (M^+). HRMS (EI): m/z calcd for $C_{16}H_{21}NO_3$: 275.1521; found: 275.1516.

*Ethyl (2-(3-Hydroxy-3-phenylprop-1-yn-1-yl)phenyl)carbamate (**14e**).* Yield: 268.7 mg, 91%; pale yellow solid; mp 55−56 °C. ^{1}H NMR ($CDCl_3$) δ: 8.14 (1H, br s), 7.63 (2H, d, J = 7.6 Hz), 7.45−7.31 (6H, m), 6.99 (1H, t, J = 7.6 Hz), 5.77 (1H, d, J = 6.2 Hz), 4.23 (2H, q, J = 7.0 Hz), 2.45 (1H, br s), 1.32 (3H, t, J = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ: 153.3, 140.4, 139.4, 131.9, 130.0, 128.8, 128.6, 126.5, 122.4, 117.8, 110.5, 95.9, 81.8, 65.1, 61.4, 14.5. IR ($CHCl_3$, cm^{-1}) 3689, 3590, 3405, 2216, 1734, 1583, 1523, 1451, 1377, 1307, 1240, 1196, 1063, 1043, 960, 832. MS (EI): m/z = 295 (M^+). HRMS (EI): m/z calcd for $C_{18}H_{17}NO_3$: 295.1208; found: 295.1210.

*Ethyl (2-((1-Hydroxycyclohexyl)ethynyl)phenyl)carbamate (**14g**).* Yield: 250 mg, 87%; brown solid; mp 84−86 °C. ^{1}H NMR ($CDCl_3$) δ: 8.13 (1H, br s), 7.37 (1H, d, J = 7.6 Hz), 7.36 (1H, br s), 7.32 (1H, t, J = 7.9 Hz), 6.98 (1H, t, J = 7.6 Hz), 4.24 (2H, q, J = 6.8 Hz), 2.14 (1H, s), 2.06 (2H, d, J = 12.4 Hz), 1.81−1.58 (8H, m), 1.32 (3H, t, J = 6.8 Hz). ^{13}C NMR ($CDCl_3$) δ: 153.3, 139.1, 131.6, 129.6, 122.3, 117.6, 111.0, 100.1, 79.6, 69.3, 61.3, 40.0, 25.1, 23.5, 14.5. IR ($CHCl_3$, cm^{-1}) 3594, 3402, 2940, 2860, 1734, 1583, 1522, 1454, 1308, 1238, 1197, 1063, 962. MS (EI): m/z = 287 (M^+). HRMS (EI): m/z calcd for $C_{17}H_{21}NO_3$: 287.1521; found: 287.1520.

General Procedure for Tandem Meyer−Schuster Rearrangement/1,4-Addition. To a solution of propargyl alcohol **1** (0.4 mmol) in 1,2-dichloroethane (2 mL) was added EtOH (4 mmol) and $Bi(OTf)_3$ (0.02 mmol), and the mixture was stirred at 70 °C. After filtration over a short pad of silica gel, the solvent was removed under reduced pressure. The crude product was purified by column chromatography on silica gel (hexane/ethyl acetate as an eluent) to give the product.

*1,5-Bis(4-methoxyphenyl)-2-methylenepentane-1,5-dione (**4**).* Yield: 15 mg, 23%; colorless plate; mp 73−74 °C. ^{1}H NMR ($CDCl_3$) δ: 7.96 (2H, d, J = 8.9 Hz), 7.79 (2H, d, J = 8.9 Hz), 6.92 (4H, d, J = 8.9 Hz), 5.85 (1H, s), 5.58 (1H, s), 3.87 (3H, s), 3.86 (3H, s), 3.17 (2H, t, J = 7.4 Hz), 2.89 (2H, t, J = 7.4 Hz). ^{13}C NMR ($CDCl_3$) δ: 197.9, 197.0, 163.5, 163.2, 147.0, 132.0, 130.4, 130.2, 129.9, 124.8, 113.7, 113.5, 55.5, 36.8, 28.1. IR ($CHCl_3$, cm^{-1}) 2967, 2938, 2842, 1675, 1649, 1601, 1576, 1510, 1464, 1442, 1420, 1308, 1259, 1170, 1032, 989, 977 844. MS (EI): m/z = 324 (M^+). HRMS (EI): m/z calcd for $C_{20}H_{20}O_4$: 324.1362; found: 324.1363. Crystals for X-ray diffraction analysis were obtained by recrystallization from $CHCl_3$−hexane. Crystal data for **4a** (CCDC 1015377): $C_{20}H_{20}O_4$, M = 324.38, monoclinic, space group $P21/c$, colorless block, a = 18.637(4) Å, b = 7.6745(16) Å, c = 11.725(3) Å, β = 101.421(16)°, V = 1643.9(7) Å, Z = 4, and Dc = 1.311 g cm^{-3}. The reflection data of 2791 reflections with $0 < \theta < 30°$ were collected on a Rigaku RAXIS-RAPID diffractometer using monochromated CuK_α radiation and an ω-2θ scan technique ($-22 \le h \le 21$, $-9 \le k \le 9$, $-12 \le l \le 11$). The structure was solved by the direct method and refined by the full-matrix least-squares method. The final R value was 0.0421 for 2791 observed reflections (wR = 0.0717, *Chebychev polynomial with 3 parameters*, 66.6594, 85.0929, 19.0744).

*Ethyl (4-(3-Ethoxypropanoyl)phenyl)carbamate (**7a**).* Yield: 96.6 mg, 91%; white solid; mp 103−105 °C. ^{1}H NMR ($CDCl_3$) δ: 7.95 (2H, d, J = 8.9 Hz), 7.47 (2H, d, J = 8.2 Hz), 6.76 (1H, br s), 4.25 (2H, q, J = 7.0 Hz), 3.85 (2H, t, J = 6.7 Hz), 3.53 (2H, q, J = 7.2 Hz), 3.22 (2H, t, J = 6.7 Hz), 1.33 (3H, t, J = 7.0 Hz), 1.20 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 197.1, 153.1, 142.5, 131.8, 129.7, 117.5, 66.5, 65.8, 61.6, 38.6, 15.1, 14.4. IR ($CHCl_3$, cm^{-1}) 3432, 2981, 2874, 1738, 1676, 1605, 1587, 1528, 1524, 1503, 1412, 1380, 1323, 1312, 11239, 1180, 1107, 1063, 988, 849. MS (EI): m/z = 265 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{19}NO_4$: 265.1314; found: 265.1317.

*3-Ethoxy-1-(p-tolyl)propan-1-one (**7b**).* Yield: 36 mg, 47%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.87 (2H, d, J = 7.8 Hz), 7.26 (2H, d, J = 7.8 Hz), 3.86 (2H, td, J = 6.9, 1.4 Hz), 3.54 (2H, q, J = 6.8 Hz), 3.24 (2H, t, J = 6.9 Hz), 2.41 (3H, s), 1.20 (3H, td, J = 6.8, 1.4 Hz). ^{13}C NMR ($CDCl_3$) δ: 198.0, 143.9, 134.5, 129.2, 128.2, 66.5, 65.8, 38.7, 21.6, 15.1. IR ($CHCl_3$, cm^{-1}) 2979, 2874, 1680, 1607, 1380, 1362, 1328, 1236, 1197, 1181, 1107, 979. MS (EI): m/z = 192 (M^+). HRMS (EI): m/z calcd for $C_{12}H_{16}O_2$: 192.1150; found: 192.1151.

*3-(Benzyloxy)-1-(4-methoxyphenyl)propan-1-one (**8b**).* Yield: 87.2 mg, 81%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.95 (2H, d, J = 8.6 Hz), 7.33−7.33 (4H, m), 7.29−7.26 (1H, m), 6.93 (2H, d, J = 8.6 Hz), 4.56 (2H, s), 3.92 (2H, t, J = 6.5 Hz), 3.87 (3H, s), 3.25 (2H, t, J = 6.5 Hz). ^{13}C NMR ($CDCl_3$) δ: 196.9, 163.5, 138.2, 130.4, 130.1, 128.4, 127.7, 127.6, 113.7, 73.3, 65.9, 55.5, 38.6. IR ($CHCl_3$, cm^{-1}) 2869, 1674, 1601, 1576, 1511, 1455, 1421, 1367, 1316, 1261, 1171, 1101, 1030, 985. MS (EI): m/z = 270 (M^+). HRMS (EI): m/z calcd for $C_{17}H_{18}O_3$: 270.1256; found: 270.1257.

*3-(Allyloxy)-1-(4-methoxyphenyl)propan-1-one (**8c**).* Yield: 76 mg, 86%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.96 (2H, d, J = 8.6 Hz), 6.94 (2H, d, J = 8.6 Hz), 5.93−5.89 (1H, m), 5.28 (1H, dd, J = 17.2, 2.1 Hz), 5.18 (1H, dd, J = 10.3, 1.4 Hz), 4.02 (2H, d, J = 6.2 Hz), 3.88−3.87 (5H, m), 3.23 (2H, t, J = 6.9 Hz). ^{13}C NMR ($CDCl_3$) δ: 196.8, 163.5, 134.6, 130.4, 130.1, 117.1, 113.7, 72.1, 65.7, 55.4, 38.5. IR ($CHCl_3$, cm^{-1}) 2912, 2873, 1675, 1601, 1577, 1511, 1464, 1421, 1364,

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1316, 1261, 1171, 1100, 1033, 988, 933. MS (EI): m/z = 220 (M^+). HRMS (EI): m/z calcd for $C_{13}H_{16}O_3$: 220.1099; found: 220.1095.

*1-(4-Methoxyphenyl)-3-(prop-2-yn-1-yloxy)propan-1-one (**8d**).* Yield: 48.2 mg, 55%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.95 (2H, d, J = 8.9 Hz), 6.94 (2H, d, J = 8.9 Hz), 4.19 (2H, d, J = 2.3 Hz), 3.97 (2H, t, J = 6.5 Hz), 3.88 (3H, s), 3.24 (2H, t, J = 6.5 Hz), 2.44 (1H, t, J = 2.3 Hz). ^{13}C NMR ($CDCl_3$) δ: 196.5, 163.6, 130.4, 130.0, 113.7, 79.7, 74.5, 65.5, 58.4, 55.5, 38.2. IR ($CHCl_3$, cm^{-1}) 3308, 2912, 1675, 1601, 1577, 1511, 1465, 1443, 1421, 1363, 1333, 1316, 1260, 1170, 1103, 1033, 986, 846. MS (EI): m/z = 218 (M^+). HRMS (EI): m/z calcd for $C_{13}H_{14}O_3$: 218.0943; found: 218.0941.

*1-(4-Methoxyphenyl)-3-(2,2,2-trifluoroethoxy)propan-1-one (**8e**).* Yield: 5.5 mg, 5.2%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.95 (2H, d, J = 8.9 Hz), 6.95 (2H, d, J = 8.9 Hz), 4.06 (2H, t, J = 6.4 Hz), 3.89 (2H, q, J = 8.7 Hz), 3.88 (3H, s), 3.25 (2H, t, J = 6.4 Hz). ^{13}C NMR ($CDCl_3$) δ: 196.0, 163.7, 130.4, 129.8, 124.9, 123.0, 121.2, 113.8, 69.1, 68.9, 68.7, 68.5, 68.1, 55.5, 38.3. IR ($CHCl_3$, cm^{-1}) 3691, 2938, 1676, 1601, 1576, 1512, 1465, 1420, 1309, 1280, 1262, 1170, 1032, 990. MS (EI): m/z = 262 (M^+). HRMS (EI): m/z calcd for $C_{12}H_{13}F_3O_3$: 262.0817; found: 262.0826.

*3-(2-Methoxyethoxy)-1-(4-methoxyphenyl)propan-1-one (**8f**).* Yield: 73.6 mg, 77%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.95 (2H, d, J = 8.9 Hz), 6.93 (2H, d, J = 8.9 Hz), 3.91 (2H, t, J = 6.5 Hz), 3.87 (3H, s), 3.65 (2H, dd, J = 3.1, 1.6 Hz), 3.54 (2H, dd, J = 3.2, 1.6 Hz), 3.38 (3H, s), 3.26 (2H, t, J = 6.5 Hz). ^{13}C NMR ($CDCl_3$) δ: 196.8, 163.5, 130.3, 130.0, 113.7, 71.8, 70.4, 66.6, 59.0, 55.4, 38.4. IR ($CHCl_3$, cm^{-1}) 2895, 1675, 1601, 1577, 1511, 1465, 1420, 1363, 1261, 1171, 1032, 987, 844. MS (EI): m/z = 238 (M^+). HRMS (EI): m/z calcd for $C_{13}H_{18}O_4$: 238.1205; found: 238.1205.

*2-(3-(4-Methoxyphenyl)-3-oxopropoxy)ethyl Acetate (**8g**).* Yield: 42.6 mg, 40%; colorless oil. ^{1}H NMR ($CDCl^3$) δ: 7.95 (2H, d, J = 8.6 Hz), 6.94 (2H, d, J = 8.6 Hz), 4.21 (2H, t, J = 4.5 Hz), 3.92 (2H, t, J = 6.5 Hz), 3.88 (3H, s), 3.71−3.69 (2H, m), 3.24 (2H, t, J = 6.5 Hz), 2.07 (3H, s). ^{13}C NMR ($CDCl_3$) δ: 196.6, 171.0, 163.5, 130.3, 130.0, 113.7, 69.0, 66.6, 63.5, 55.4, 38.3, 20.9. IR ($CHCl_3$, cm^{-1}) 2965, 1733, 1674, 1601, 1576, 1511, 1464, 1421, 1258, 1238, 1171, 1126, 1049, 987. MS (EI): m/z = 266 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{18}O_5$: 266.1154; found: 266.1154.

*3-Isopropoxy-1-(4-methoxyphenyl)propan-1-one (**8h**).* Yield: 68.2 mg, 77%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.96 (2H, d, J = 8.9 Hz), 6.93 (2H, d, J = 8.9 Hz), 3.87 (3H, s), 3.84 (2H, t, J = 6.9 Hz), 3.65−3.61 (1H, m), 3.20 (2H, t, J = 6.9 Hz), 1.16 (6H, d, J = 6.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 197.1, 163.4, 130.4, 130.2, 113.6, 71.8, 63.5, 55.4, 38.9, 22.0. IR ($CHCl_3$, cm^{-1}) 2974, 1675, 1601, 1511, 1465, 1420, 1346, 1261, 1170, 1126, 1077, 1032, 987, 841. MS (EI): m/z = 222 (M^+). HRMS (EI): m/z calcd for $C_{13}H_{18}O_3$: 222.1256; found: 222.1261.

*3-(tert-Butoxy)-1-(4-methoxyphenyl)propan-1-one (**8i**).* Yield: 25.8 mg, 27%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 7.96 (2H, d, J = 8.9 Hz), 6.93 (2H, d, J = 8.9 Hz), 3.87 (3H, s), 3.79 (2H, t, J = 7.2 Hz), 3.17 (2H, t, J = 7.2 Hz), 1.20 (9H, s). ^{13}C NMR ($CDCl_3$) δ: 197.5, 163.4, 130.4, 130.3, 113.6, 73.1, 57.5, 55.4, 39.4, 27.5. IR ($CHCl_3$, cm^{-1}) 3689, 2977, 1674, 1601, 1511, 1464, 1420, 1396, 1366, 1331, 1259, 1170, 1075, 1033, 987, 845. MS (EI): m/z = 236 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{20}O_3$: 236.1412; found: 236.1408.

*3-Ethoxy-1-(4-methoxyphenyl)-5-methylhexan-1-one (**10b**).* Yield: 7 mg, 6.6%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 7.96 (2H, d, J = 8.6 Hz), 6.94 (2H, d, J = 8.6 Hz), 4.03−3.99 (1H, m), 3.88 (3H, s), 3.56−3.45 (2H, m), 3.24 (1H, dd, J = 15.8, 5.9 Hz), 2.87 (1H, dd, J = 15.8, 5.9 Hz), 1.82−1.75 (1H, m), 1.56−1.51 (1H, m), 1.32−1.27 (1H, m), 1.12 (3H, t, J = 6.9 Hz), 0.94 (3H, d, J = 6.9 Hz), 0.92 (3H, d, J = 6.9 Hz). ^{13}C NMR ($CDCl_3$) δ: 197.9, 163.5, 130.6, 130.5, 113.7, 74.7, 65.1, 55.5, 44.9, 44.0, 24.7, 23.3, 22.3, 15.6. IR ($CHCl_3$, cm^{-1}) 2969, 1672, 1576, 1511, 1457, 1420, 1311, 1262, 1171, 1085, 1031, 835. MS (EI): m/z = 264 (M^+). HRMS (EI): m/z calcd for $C_{16}H_{24}O_3$: 264.1725; found: 264.1728.

*(E)-1-(4-Methoxyphenyl)-5-methylhex-2-en-1-one (**11b**).* Yield: 61.7 mg, 70%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 7.96 (2H, d, J = 8.7 Hz), 7.06−7.01 (1H, m), 6.95 (2H, d, J = 8.7 Hz), 6.88 (1H, d, J = 15.1 Hz), 3.88 (3H, s), 2.20 (2H, t, J = 7.2 Hz), 1.86−1.80 (1H, m), 0.96 (6H, d, J = 6.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 189.0, 163.2, 147.8, 130.8, 130.8, 126.5, 113.7, 55.4, 42.1, 28.0, 22.4. IR ($CHCl_3$, cm^{-1}) 3524, 2961, 2871, 2842, 1664, 1617, 1600, 1575, 1511, 1465, 1420, 1351, 1307, 1260, 1171, 1031, 1003, 982, 893, 843. MS (EI): m/z = 218 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{18}O_2$: 218.1307; found: 218.1306.

General Procedure for Heterocyclic Compound Synthesis. To a solution of propargyl alcohol **1** (0.3 mmol) in 1,2-dichloroethane (1.5 mL) was added EtOH (1.5 mmol) and $Bi(OTf)_3$ (0.015 mmol), and the mixture was stirred at 70 °C. After filtration over a short pad of silica gel, the solvent was removed under reduced pressure. The crude product was purified by column chromatography on silica gel (hexane/ethyl acetate as an eluent) to give the product.

*Ethyl (2-Acryloylphenyl)carbamate (**15b**).* Yield: 16.8 mg, 26%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 10.92 (1H, s), 8.47 (1H, d, J = 8.1 Hz), 7.86 (1H, dd, J = 7.8, 1.7 Hz), 7.56 (1H, t, J = 8.1 Hz), 7.22 (1H, dd, J = 16.8, 10.9 Hz), 7.08 (1H, t, J = 7.8 Hz), 6.44 (1H, dd, J = 16.8, 1.6 Hz), 5.94 (1H, dd, J = 10.9, 1.6 Hz), 4.23 (2H, q, J = 7.1 Hz), 1.33 (3H, t, J = 6.9 Hz). ^{13}C NMR ($CDCl_3$) δ: 193.6, 153.9, 141.7, 134.9, 133.1, 131.0, 130.4, 121.9, 121.3, 119.5, 61.2, 14.5. IR ($CHCl_3$, cm^{-1}) 3292, 2984, 1729, 1653, 1605, 1583, 1525, 1453, 1307, 1239, 1197, 1166, 1095, 1065, 994. MS (EI): m/z = 219 (M^+). HRMS (EI): m/z calcd for $C_{12}H_{13}NO_3$: 219.0895; found: 219.0900.

*Ethyl 4-Oxo-3,4-dihydroquinoline-1(2H)-carboxylate (**16b**).* Yield: 56.2 mg, 86%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 8.00 (1H, dd, J = 7.9, 1.8 Hz), 7.81 (1H, d, J = 8.2 Hz), 7.52 (1H, td, J = 7.9, 1.8 Hz), 7.19 (1H, t, J = 7.6 Hz), 4.31 (2H, q, J = 7.2 Hz), 4.22 (2H, t, J = 6.5 Hz), 2.79 (2H, t, J = 6.5 Hz), 1.36 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 193.9, 153.8, 143.7, 134.1, 127.3, 124.9, 124.1, 123.4, 62.6, 44.4, 38.9, 14.4. IR ($CHCl_3$, cm^{-1}) 2986, 1684, 1602, 1575, 1480, 1466, 1458, 1405, 1380, 1352, 1330, 1318, 1305, 1239, 1196, 1135, 1095, 1057, 1029, 963, 861. MS (EI): m/z = 219 (M^+). HRMS (EI): m/z calcd for $C_{12}H_{13}NO_3$: 219.0895; found: 219.0894.

*Ethyl 2-Methyl-4-oxo-3,4-dihydroquinoline-1(2H)-carboxylate (**16c**).* Yield: 62.1 mg, 87%; yellow oil. ^{1}H NMR ($CDCl_3$) δ: 8.00 (1H, dd, J = 7.9, 1.8 Hz), 7.82 (1H, d, J = 8.2 Hz), 7.53 (1H, td, J = 7.9, 1.8 Hz), 7.16 (1H, t, J = 7.6 Hz), 5.19−5.14 (1H, m), 4.37−4.27 (2H, m), 3.06 (1H, dd, J = 17.2, 5.5 Hz), 2.58 (1H, dd, J = 17.2, 2.1 Hz), 1.37 (3H, t, J = 7.2 Hz), 1.24 (3H, d, J = 6.9 Hz). ^{13}C NMR ($CDCl_3$) δ: 193.3, 153.8, 141.0, 134.4, 126.7, 124.2, 124.1, 123.7, 62.5, 49.7, 44.3, 17.7, 14.4. IR ($CHCl_3$, cm^{-1}) 2985, 1684, 1602, 1577, 1481, 1462, 1398, 1387, 1372, 1326, 1305, 1277, 1129, 1107, 1063, 1052, 1029. MS (EI): m/z = 233 (M^+). HRMS (EI): m/z calcd for $C_{13}H_{15}NO_3$: 233.1052; found: 233.1054.

*Ethyl 2-Isobutyl-4-oxo-3,4-dihydroquinoline-1(2H)-carboxylate (**16d**).* Yield: 69.5 mg, 84%; pale yellow oil. ^{1}H NMR ($CDCl_3$) δ: 7.98 (1H, dd, J = 7.9, 1.7 Hz), 7.73 (1H, br s), 7.53 (1H, td, J = 7.7, 1.6 Hz), 7.18 (1H, t, J = 7.6 Hz), 5.08−5.07 (1H, m), 4.31 (2H, q, J = 7.2 Hz), 3.06 (1H, dd, J = 17.2, 5.5 Hz), 2.59 (1H, dd, J = 17.5, 1.7 Hz), 1.57−1.55 (2H, m), 1.36 (3H, t, J = 7.2 Hz), 1.26−1.22 (1H, m), 0.95 (3H, d, J = 6.2 Hz), 0.81 (3H, d, J = 6.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 193.5, 154.1, 141.0, 134.2, 126.6, 124.9, 124.9, 124.0, 62.4, 52.0, 43.5, 40.4, 25.0, 22.7, 22.0, 14.3. IR ($CHCl_3$, cm^{-1}) 2962, 2915, 1684, 1602, 1577, 1480, 1462, 1400, 1388, 1373, 1340, 1323, 1291, 1268, 1237, 1132, 1053, 971. MS (EI): m/z = 275 (M^+). HRMS (EI): m/z calcd for $C_{16}H_{21}NO_3$: 275.1521; found: 275.1525.

*Ethyl 4-Oxo-2-phenyl-3,4-dihydroquinoline-1(2H)-carboxylate (**16e**).* Yield: 70 mg, 79%; yellow solid; mp 91−93 °C. ^{1}H NMR ($CDCl_3$) δ: 7.89 (1H, dd, J = 7.9, 1.7 Hz), 7.80 (1H, d, J = 8.2 Hz), 7.47 (1H, t, J = 7.9 Hz), 7.22−7.21 (4H, m), 7.17−7.16 (1H, m), 7.08 (1H, t, J = 7.6 Hz), 6.22 (1H, t, J = 3.8 Hz), 4.43−4.35 (2H, m), 3.32−3.31 (2H, m), 1.39 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 192.8, 154.4, 141.6, 138.1, 134.4, 128.5, 127.4, 126.8, 126.5, 124.9, 124.3, 123.9, 62.9, 55.9, 42.3, 14.4. IR ($CHCl_3$, cm^{-1}) 2986, 1684, 1603, 1481, 1461, 1397, 1380, 1322, 1303, 1237, 1133, 1051, 1042, 953. MS (EI): m/z = 295 (M^+). HRMS (EI): m/z calcd for $C_{18}H_{17}NO_3$: 295.1208; found: 295.1207.

*Ethyl 2,2-Dimethyl-4-oxo-3,4-dihydroquinoline-1(2H)-carboxylate (**16f**).* Yield: 59.7 mg, 80%; white solid; mp 45−46 °C. ^{1}H NMR ($CDCl_3$) δ: 7.95 (1H, d, J = 7.6 Hz), 7.45 (1H, td, J = 7.9, 1.4

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Hz), 7.29 (1H, d, J = 8.2 Hz), 7.08 (1H, t, J = 7.6 Hz), 4.30 (2H, q, J = 7.2 Hz), 2.76 (2H, s), 1.52 (6H, s), 1.35 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 193.7, 155.0, 144.4, 134.4, 126.6, 123.5, 122.6, 122.5, 62.3, 59.1, 53.0, 26.9, 14.2. IR ($CHCl_3$, cm^{-1}) 2983, 1716, 1685, 1604, 1480, 1461, 1372, 1341, 1318, 1286, 1237, 1168, 1125, 1074, 1023. MS (EI): m/z = 247 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{17}NO_3$: 247.1208; found: 247.1214.

*Ethyl 4′-Oxo-3′,4′-dihydro-1′H-spiro[cyclohexane-1,2′-quinoline]-1′-carboxylate (**16g**).* Yield: 26.2 mg, 30%; white solid; mp 83−85 °C. ^{1}H NMR ($CDCl_3$) δ: 7.91 (1H, dd, J = 7.6, 1.4 Hz), 7.50 (1H, t, J = 6.9 Hz), 7.34 (1H, d, J = 7.6 Hz), 7.24 (1H, t, J = 7.6 Hz), 4.13 (2H, q, J = 7.2 Hz), 2.82 (2H, s), 2.39 (2H, br s), 1.65−1.39 (8H, m), 1.21 (3H, t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$) δ: 195.2, 154.6, 144.2, 133.5, 127.8, 126.1, 125.2, 62.1, 61.8, 50.5, 35.9, 25.4, 22.2, 14.2. IR ($CHCl_3$, cm^{-1}) 2940, 1712, 1684, 1603, 1478, 1460, 1397, 1371, 1308, 1275, 1117, 1099, 1089, 1038, 1027. MS (EI): m/z = 287 (M^+). HRMS (EI): m/z calcd for $C_{17}H_{21}NO_3$: 287.1521; found: 287.1525.

*3-Ethoxy-1-(2-hydroxyphenyl)propan-1-one (**17a**).* Yield: 20.8 mg, 36%; colorless oil. ^{1}H NMR ($CDCl_3$) δ: 12.24 (1H, s), 7.78 (1H, d, J = 8.2 Hz), 7.47 (1H, t, J = 7.6 Hz), 6.98 (1H, d, J = 8.9 Hz), 6.91 (1H, t, J = 7.6 Hz), 3.86 (2H, t, J = 6.5 Hz), 3.54 (2H, q, J = 7.1 Hz), 3.29 (2H, t, J = 6.5 Hz), 1.20 (3H, t, J = 7.1 Hz). ^{13}C NMR ($CDCl_3$) δ: 204.5, 162.5, 136.5, 130.1, 119.6, 119.0, 118.5, 66.6, 65.3, 38.6, 15.1. IR ($CHCl_3$, cm^{-1}) 3689, 2875, 1640, 1616, 1488, 1449, 1382, 1355, 1289, 1269, 1158, 1107, 988. MS (EI): m/z = 194 (M^+). HRMS (EI): m/z calcd for $C_{11}H_{14}O_3$: 194.0943; found: 194.0937.

*Ethyl (2-(3-Ethoxypropanoyl)phenyl)carbamate (**17b**).* Yield: 10.1 mg, 13%; white solid; mp 43−44 °C. ^{1}H NMR ($CDCl_3$) δ: 11.12 (1H, br s), 8.48 (1H, d, J = 8.2 Hz), 7.91 (1H, d, J = 7.6 Hz), 7.54 (1H, t, J = 7.2 Hz), 7.06 (1H, t, J = 7.2 Hz), 4.22 (2H, q, J = 7.2 Hz), 3.84 (2H, t, J = 6.5 Hz), 3.54 (2H, q, J = 7.0 Hz), 3.30 (2H, t, J = 6.5 Hz), 1.32 (3H, t, J = 7.2 Hz), 1.21 (3H, t, J = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ: 202.3, 153.9, 141.5, 134.9, 130.9, 121.3, 121.3, 119.2, 66.6, 65.6, 61.1, 40.0, 15.1, 14.5. IR ($CHCl_3$, cm^{-1}) 3269, 2981, 2874, 1729, 1653, 1584, 1526, 1454, 1380, 1361, 1306, 1241, 1167, 1107, 1064, 981. MS (EI): m/z = 265 (M^+). HRMS (EI): m/z calcd for $C_{14}H_{19}NO_4$: 265.1314; found: 265.1314.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

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

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Cyclization of alkynes: (a) Gilmore, K.; Alabugin, I. V. *Chem. Rev.* **2011**, *111*, 6513−6556. (b) Godoi, B.; Schumacher, R. F.; Zeni, G. *Chem. Rev.* **2011**, *111*, 2937−2980. (c) Guo, L.-N.; Duan, X.-H.; Liang, Y.-M. *Acc. Chem. Res.* **2011**, *44*, 111−122.

(2) Click chemistry: (a) Hein, J. E.; Fokin, V. V. *Chem. Soc. Rev.* **2010**, *39*, 1302−1315. (b) Meldal, M.; Tornøe, C. W. *Chem. Rev.* **2008**, *108*, 2952−3015.

(3) Transition-metal-catalyzed reaction: (a) Chinchilla, R.; Nájera, C. *Chem. Rev.* **2014**, *114*, 1783−1826. (b) Villar, H.; Frings, M.; Bolm, C. *Chem. Soc. Rev.* **2007**, *36*, 55−66. (c) Fürstner, A.; Davies, P. W. *Chem. Commun.* **2005**, 2307−2320. (d) Zeni, G.; Larock, R. C. *Chem. Rev.* **2004**, *104*, 2285−2310.

(4) Reaction of propargyl alcohol: Zhu, Y.; Sun, L.; Lu, P.; Wang, Y. *ACS Catal.* **2014**, *4*, 1911−1925.

(5) (a) Okamoto, N.; Takeda, K.; Yanada, R. *Org. Synth.* **2014**, *91*, 27−38. (b) Okamoto, N.; Ishikura, M.; Yanada, R. *Org. Lett.* **2013**, *15*, 2571−2573. (c) Okamoto, N.; Yanada, R. *J. Org. Chem.* **2012**, *77*, 3944−3951. (d) Okamoto, N.; Miwa, Y.; Minami, H.; Takeda, K.; Yanada, R. *J. Org. Chem.* **2011**, *76*, 9133−9138. (e) Okamoto, N.; Takeda, K.; Ishikura, M.; Yanada, R. *J. Org. Chem.* **2011**, *76*, 9139−9143. (f) Okamoto, N.; Takeda, K.; Yanada, R. *J. Org. Chem.* **2010**, *75*, 7615−7625. (g) Okamoto, N.; Miwa, Y.; Minami, H.; Takeda, K.; Yanada, R. *Angew. Chem., Int. Ed.* **2009**, *48*, 9693−9696.

(6) (a) Meyer, K. H.; Schuster, K. *Chem. Ber.* **1922**, *55*, 819−823. (b) Swaminathan, S.; Narayanan, K. V. *Chem. Rev.* **1971**, *71*, 429−438. (c) Edens, M.; Boerner, D.; Chase, C. R.; Nass, D.; Schiavelli, M. D. *J. Org. Chem.* **1977**, *42*, 3403−3408. (d) Engel, D. A.; Dudley, G. B. *Org. Biomol. Chem.* **2009**, *7*, 4149−4158.

(7) (a) Xiong, Y.-P.; Wu, M.-Y.; Zhang, X.-Y.; Ma, C.-L.; Huang, L.; Zhao, L.-J.; Tan, B.; Liu, X.-Y. *Org. Lett.* **2014**, *16*, 1000−1003. (b) Yu, Y.; Yang, W.; Pflästerer, D.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2014**, *53*, 1144−1147. (c) Collins, B. S. L.; Suero, M. G.; Gaunt, M. J. *Angew. Chem., Int. Ed.* **2013**, *52*, 5799−5802. (d) Hansmann, M. M.; Hashmi, A. S. K.; Lautens, M. *Org. Lett.* **2013**, *15*, 3226−3229. (e) Laali, K. K.; Nandi, G. C.; Borosyky, G. L.; Kumar, G. G. K. S. N. *Eur. J. Org. Chem.* **2013**, 5455−5463. (f) Mattia, E.; Porta, A.; Merlini, V.; Zanoni, G.; Vidari, G. *Chem. Eur. J.* **2012**, *18*, 11894−11898. (g) Pennell, M. N.; Unthank, M. G.; Turner, P.; Sheppard, T. D. *J. Org. Chem.* **2011**, *76*, 1479−1482. (h) Sugawara, Y.; Yamada, W.; Yoshida, S.; Ikeno, T.; Yamada, T. *J. Am. Chem. Soc.* **2007**, *129*, 12902−12903. (i) Engel, D. A.; Dudley, G. B. *Org. Lett.* **2006**, *8*, 4027−4029.

(8) (a) Bhuvaneswari, S.; Jeganmohan, M.; Cheng, C.-H. *Chem.—Asian J.* **2010**, *5*, 141−146. (b) Egi, M.; Yamaguchi, Y.; Fujiwara, N.; Akai, S. *Org. Lett.* **2008**, *10*, 1867−1870.

(9) (a) Nitsch, D.; Bach, T. *J. Org. Chem.* **2014**, *79*, 6372−6379. (b) Nitsch, D.; Huber, S. M.; Pöthig, A.; Narayanan, A.; Olah, G. A.; Prakash, G. K. S.; Bach, T. *J. Am. Chem. Soc.* **2014**, *136*, 2851−2857. (c) Murai, M.; Origuchi, K.; Takai, K. *Org. Lett.* **2014**, *16*, 3828−3831. (d) Mandadapu, V.; Wu, F.; Day, A. I. *Org. Lett.* **2014**, *16*, 1275−1277. (e) Raju, B. C.; Prasad, K. V.; Saidachary, G.; Sridhar, B. *Org. Lett.* **2014**, *16*, 420−423. (f) Kitanosono, T.; Ollevier, T.; Kobayashi, S. *Chem.—Asian J.* **2013**, *8*, 3051−3062. (g) Schneider, A. E.; Manolikakes, G. *Synlett* **2013**, *24*, 2057−2060. (h) Tran, P. H.; Duus, F.; Le, T. N. *Tetrahedron Lett.* **2012**, *53*, 222−224.

(10) (a) Ollevier, T. *Org. Biomol. Chem.* **2013**, *11*, 2740−2755. (b) Bothwell, J. M.; Krabbe, S. W.; Mohan, R. S. *Chem. Soc. Rev.* **2011**, *40*, 4649−4707. (c) Gaspard-Iloughmane, H.; Le Roux, C. *Eur. J. Org. Chem.* **2004**, 2517−2532. (d) Leonard, N. M.; Wieland, L. C.; Mohan, R. S. *Tetrahedron* **2002**, *58*, 8373−8397.

(11) CCDC 1015377 (**4**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.