DOI: 10.1002/adsc.200800088

Studies on Electrophilic Interaction of 2,3-Allenols with Electrophilic Halogen Reagents: Selective Synthesis of 2,5-Dihydrofurans, 3-Halo-3-alkenals, or 2-Halo-2-alkenyl Ketones

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Received: February 11, 2008; Published online: May 19, 2008

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Abstract: The reaction of primary 2,3-allenols with iodine (I_2) afforded 2,5-dihydrofurans while that of readily available 1-aryl or 1-methyl substituted 2,3-allenols with bromine (Br_2), *N*-bromosuccinimide (NBS), I_2 or *N*-iodosuccinimide (NIS) formed the not easily available but synthetically useful 3-halo-3-alkenals and 2-halo-2-alkenyl ketones with good selectivity and yields *via* a sequential electrophilic interaction of X^+ with the allene moiety, 1,2-aryl or 1,2-proton shift, and H^+ elimination process.

Keywords: alcohols; aldehydes; allenes; electrophilic addition; halogens; ketones

Introduction

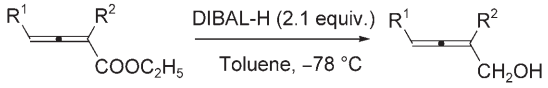
Elecotrophilic additions of alkenes and alkynes with "X^+" have provided many useful methodologies for the efficient synthesis of halides.[1] The electrophilic addition of allenes with "X^+" is also quite attractive since 2-haloallylic halides or alcohols are usually formed.[2] The electrophilic addition of alkyl-substituted allenes afforded terminal- or center-attack products, depending on the structures of the allenes and electrophiles:[3] Chlorination of propadiene afforded a mixture of 2,3-dichloro-1-propene and propargylic chloride[4] while that of 3-methyl-1,2-butadiene afforded a mixture of regioisomeric 2,3-dichloro-3-methyl-1-butene and 1,2-dichloro-3-methyl-2-butene.[5] The manganese-mediated chlorination of monosubstituted allenes afforded a mixture of 2,3-dichloro-1-alkenes and 1,2-dichloro-2-alkenes.[6] Bromination of phenyl-1,2-propadiene in MeOH at 0 °C also led to a regioisomeric mixture of 2-bromoallylic methyl ethers, however, in a non-polar solvent such as CS_2, CH_2Cl_2, or CCl_4 only 2,3-dibromo-1-phenyl-1-propene was formed.[7] Iodination of dialkyl-substituted allenes formed 1,2-diiodo-2-alkenes in $CHCl_3$ or CH_2Cl_2 whereas in the presence of $Hg(OAc)_2$ in MeOH the reaction afforded a regioisomeric mixture of 2-iodoallylic ethers.[8] In our laboratory we have obsevered that the reaction of "X^+" with functionalized allenes afforded cyclic alkenyl halides[9] or the halohydroxylation products.[10] In 1993, Friesen et al. reported that the reaction of 2,3-allenols with I_2 in Et_2O afforded 3,4-diiodo-2-alken-1-ol with a stereoselectivity of 7:1 to 9:1 (*Z*/*E*).[11] In a primary communication we have reported that the sequential electrophilic addition reaction with "X^+" and 1,2-migration of 2,3-allenols afforded 3-halo-3-enals.[12] In this paper, we report our detailed study in this area.

Results and Discussion

Preparation of the Starting Materials 2a–i

Primary 2,3-allenols **2a–i** used in this study were prepared by reduction of the related 2,3-allenates **1a–i** with DIBAL-H (Table 1).[13]

Table 1. Synthesis of primary 2,3-allenols **2a–i**.



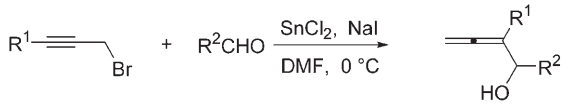
1 2

Entry	R^1	R^2	Time [h]	Yield [%] of **2a–i**
1	n-C_7H_{15}	H (**1a**)	5.3	23 (**2a**)
2	n-C_6H_{13}	CH_3 (**1b**)	2.5	36 (**2b**)
3	n-C_7H_{15}	CH_3 (**1c**)	3.8	57 (**2c**)
4	n-C_6H_{13}	n-C_3H_7 (**1d**)	6.2	70 (**2d**)
5	n-C_7H_{15}	n-C_3H_7 (**1e**)	6.7	53 (**2e**)
6	CH_3	Bn (**1f**)	3.5	32 (**2f**)
7	n-C_3H_7	Bn (**1g**)	4.8	33 (**2g**)
8	n-C_4H_9	Bn (**1h**)	3.3	38 (**2h**)
9	n-C_6H_{13}	Bn (**1i**)	3.5	40 (**2i**)

Preparation of Secondary 2,3-Allenols 5a–q

Secondary 2,3-allenols **5a–q** were prepared from the reaction of the corresponding propargylic bromides with aldehydes in the presence of NaI and $SnCl_2$ (Table 2).[14]

Table 2. Synthesis of secondary 2,3-allenols **5a–q**.

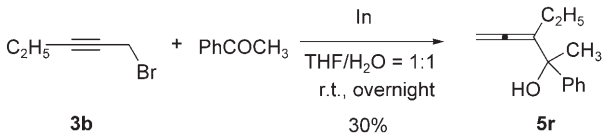


3 4 5

Entry	R^1	R^2	Time [h]	Yield [%]
1	n-C_4H_9	Ph	12	40 (**5a**)
2	n-C_4H_9	m,p-$OCH_2OC_6H_3$	15	45 (**5b**)
3	n-C_4H_9	p-$MeOC_6H_4$	10	45 (**5c**)
4	n-C_4H_9	p-MeC_6H_4	12	57 (**5d**)
5	n-C_2H_5	m,p-$OCH_2OC_6H_3$	16	44 (**5e**)
6	n-C_2H_5	p-$MeOC_6H_4$	12	66 (**5f**)
7	n-C_2H_5	p-MeC_6H_4	11	51 (**5g**)
8	allyl	m,p-$OCH_2OC_6H_3$	12	62 (**5h**)
9	allyl	p-$MeOC_6H_4$	11	41 (**5i**)
10	allyl	p-MeC_6H_4	17	56 (**5j**)
11	n-C_4H_9	α-Naphthyl	17	62 (**5k**)
12	n-C_4H_9	m-BrC_6H_4	20	58 (**5l**)
13	n-C_4H_9	p-ClC_6H_4	11	46 (**5m**)
14	n-C_4H_9	p-$NO_2C_6H_4$	17	66 (**5n**)
15	n-C_4H_9	o,p-$Cl_2C_6H_3$	20	49 (**5o**)
16	n-C_4H_9	o-ClC_6H_4	20	52 (**5p**)
17	n-C_4H_9	CH_3	10	46 (**5q**)

Preparation of Tertiary 2,3-Allenol 5r

The tertiary 2,3-allenol **5r** was prepared from the reaction of the corresponding propargylic bromide with acetophenone in the presence of In in $THF/H_2O = 1/1$ (Scheme 1).[15]



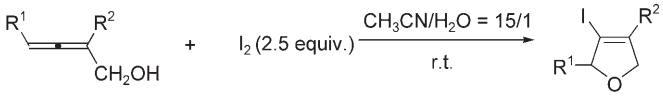
3b 30% 5r

Scheme 1.

Electrophilic Cyclization of Primary 2,3-Allenols 2 with I_2

Our initial study began with the reaction of 2-propyldeca-2,3-dien-1-ol **2d** with 2.5 equiv. of I_2 in $CH_3CN/H_2O = 15/1$ at room temperature.[12] Instead of the diiodination product,[11] 2,5-dihydrofuran **6d** was formed in 60% yield. Then, we studied the scope of this cyclization reaction with some of the typical results being summarized in Table 3. It can be concluded that differently substituted primary 2,3-allenols **2a–i** can be used to prepare the 2,4-disubstituted-3-iodo-2,5-dihydrofurans **6a–i** in moderate to good yields.

Table 3. Electrophilic cyclization of primary 2,3-allenols **2** with I_2.[a]



2 6

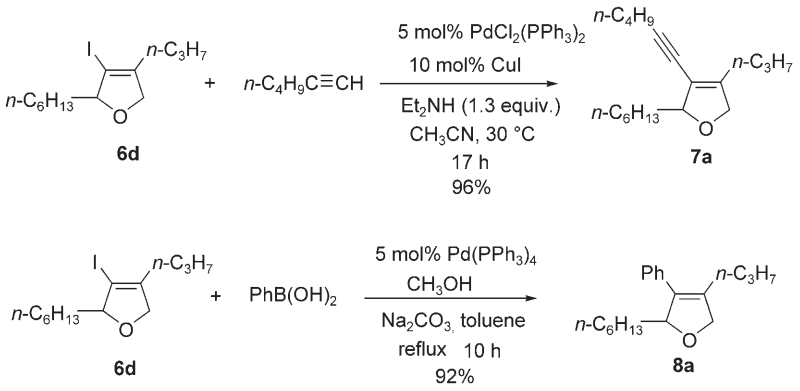
Entry	R^1	R^2	Time [h]	Isolated Yield [%] of **6**
1	n-C_7H_{15}	H (**2a**)	1.3	65 (**6a**)
2	n-C_6H_{13}	CH_3 (**2b**)	20	60 (**6b**)
3	n-C_7H_{15}	CH_3 (**2c**)	16	72 (**6c**)
4	n-C_6H_{13}	n-C_3H_7 (**2d**)	22	60 (**6d**)
5	n-C_7H_{15}	n-C_3H_7 (**2e**)	22	63 (**6e**)
6	CH_3	Bn (**2f**)	1.7	67 (**6f**)
7	n-C_3H_7	Bn (**2g**)	10	73 (**6g**)
8	n-C_4H_9	Bn (**2h**)	2.5	75 (**6h**)
9	n-C_6H_{13}	Bn (**2i**)	1.7	82 (**6i**)

[a] The reaction was carried out using 0.4–0.5 mmol of 2,3-allenols.

The carbon-iodine bond in **6d** may undergo a coupling reaction with 1-hexyne or phenylboronic acid to afford 3-hexynyl- or phenyl-substituted 2,5-dihydrofuran **7a** or **8a**, respectively, in excellent yields (Scheme 2).

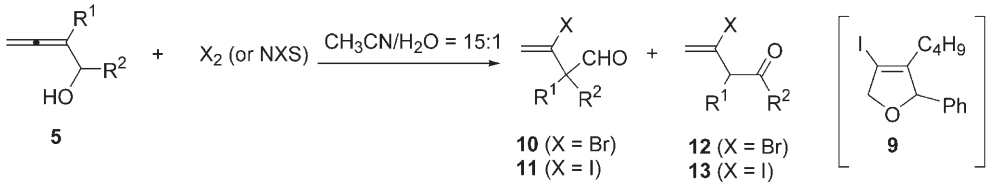
Reaction of Secondary 2,3-Allenols with X_2

However, when we tried to extend this reaction to 1-aryl-substituted 2,3-allenols, the expected 2-aryl-2,5-dihydrofuran **9** was not formed. The reaction of 1-phenyl-2-butyl-2,3-butadienol **5a** with Br_2 in aqueous



Scheme 2.

Table 4. Reaction of secondary 2,3-allenols **5** with X_2 (or NBS).



Entry	R^1	R^2	X^+ [equiv]	Temp. [°C]	Time [min]	Yield [%] of **10** or **11**	**10**/**12** or **11**/**13**[a]
1	n-C_4H_9	Ph (**5a**)	Br_2 (2)	0	30	80 (**10a**)	≥95:5
2	n-C_4H_9	m,p-$OCH_2OC_6H_3$ (**5b**)	Br_2 (2)	r.t.	50	78 (**10b**)	98:2
3			NBS (1.2)	0	30	93 (**10b**)	99:1
4			I_2 (2)	r.t.	60	80 (**11b**)	>99:1
5	n-C_4H_9	p-$MeOC_6H_4$ (**5c**)	Br_2 (2)	r.t.	90	71 (**10c**)	≥99:1
6			NBS (1.2)	r.t.	30	88 (**10c**)	99:1
7			I_2 (2)	r.t.	30	77 (**11c**)	>99:1
8			NIS (2)	r.t.	30	89 (**11c**)	>99:1
9	n-C_4H_9	p-MeC_6H_4 (**5d**)	Br_2 (1.2)	0	60	87 (**10d**)	97:3
10			NBS (1.2)	0	140	90 (**10d**)	97:3
11			I_2 (2)	0	25	68 (**11d**)	97:3
12	C_2H_5	m,p-$OCH_2OC_6H_3$ (**5e**)	Br_2 (1.2)	0	25	78 (**10e**)	>99:1
13			NBS (1.2)	0	30	84 (**10e**)	>99:1
14			I_2 (2)	r.t.	30	69 (**11e**)	>99:1
15			NIS (2)	r.t.	25	87 (**11e**)	>99:1
16	C_2H_5	p-$MeOC_6H_4$ (**5f**)	Br_2 (1.2)	0	30	80 (**10f**)	>99:1
17			NBS (1.2)	0	40	88 (**10f**)	>99:1
18			I_2 (2)	0	30	83 (**11f**)	>99:1
19	C_2H_5	p-MeC_6H_4 (**5g**)	Br_2 (1.2)	0	30	86 (**10g**)	97:3
20			NBS (1.2)	0	35	64 (**10g**)	97:3
21			I_2 (2)	0	30	55 (**11g**)	97:3
22			NIS (1.2)	r.t.	40	79 (**11g**)	96:4
23	allyl	m,p-$OCH_2OC_6H_3$ (**5h**)	Br_2 (1.2)	0	30	68 (**10h**)	>99:1
24			NBS (1.2)	0	30	88 (**10h**)	>99:1
25			I_2 (1.2)	r.t.	50	complicated	-
26	allyl	p-$MeOC_6H_4$ (**5i**)	Br_2 (1.2)	0	100	57 (**10i**)	>99:1
27			NBS (1.2)	0	50	62 (**10i**)	>99:1
28			I_2 (1.2)	r.t.	30	complicated	-
29			I_2 (1.2)	−20	25	37 (**11i**)	≥98:2
30	allyl	p-MeC_6H_4 (**5j**)	Br_2 (1.2)	0	55	50 (**10j**)	≥97:3
31			NBS (1.2)	0	60	71 (**10j**)	≥97:3
32	n-C_4H_9	α-naphthyl (**5k**)	Br_2 (2)	0	30	73 (**10k**)	90:10
33			NBS (1.2)	0	50	76 (**10k**)	93:7
34	n-C_4H_9	m-BrC_6H_4 (**5l**)	Br_2 (1.2)	r.t.	30	49 (**10l**/**12l**)	80:20
35			NBS (1.2)	0	30	45 (**10l**/**12l**)	80:20

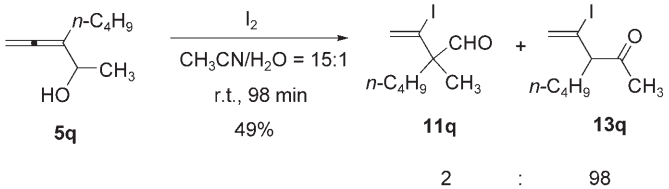
[a] The ratios of **10**/**12** or **11**/**13** determined by the ^1H NMR analysis.

CH_3CN (CH_3CN:H_2O = 15:1) afforded 3-bromo-2-(*n*-butyl)-2-phenyl-3-butenal **10a** in 77% yield.[12] By screening the most commonly used solvents and the ratio of MeCN/H_2O, it was found that a mixed solvent of MeCN/H_2O (15:1) is still the best reaction solvent.

Subsequently, the reaction of secondary 2,3-allenols with X_2 (or NXS) was performed under these conditions (Table 4). It can be concluded that 2,3-allenols with differently substituted phenyl groups at the 1-position may be used to prepare 3-halo-3-enals in good yields. By introducing the allyl group to the 2-position of 2,3-allenols, halogenation of the allylic C–C double bond was not observed, indicating a much higher reactivity of the allene functionality. For the synthesis of bromides, both Br_2 and NBS may be applied, however, the yields with NBS are usually higher than those with Br_2, probably due to the higher reactivity of Br_2 towards the remaining C=C bond (compare entries 2/3, 5/6, 12/13, 16/17, 23/24 and 30/31, Table 4). The corresponding reaction with I_2 can also occur smoothly to afford 3-iodo-3-enals **11** in good to high yields (entries 4, 7, 11, 14, 18 and 21, Table 4). The structures of the products were determined unambiguously by the X-ray diffraction study of **11b**.[12] Again for the same reason the yields with NIS are higher than those with I_2 (compare entries 7/8, 14/15, 21/22). The reaction of **5h** and **5i** with I_2 at room temperature afforded a complicated mixture (entries 25 and 28, Table 4), while the reaction of **5i** with I_2 at −20 °C afforded **11i** in 37% yield (entry 29, Table 4). In some cases, a maximum of 5% of β,γ-enone products **12** or **13** were also formed (entries 1, 9–11, 19–22, 29–31, Table 4). The ratio of **10**/**12** or **11**/**13** depends on the electronic effect of the substituent of the aryl group at the 1-position: with a more electron-donating group, the ratio of **10**/**12** or **11**/**13** is higher.

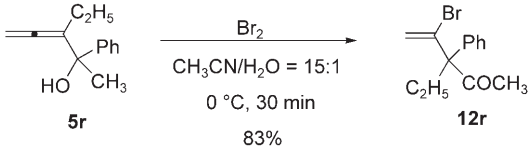
However, the substrates with a naphthyl or an aryl group bearing an electron- withdrawing group afforded a mixture of aldehydes **10**/**12** and ketones **11**/**13** with relatively poor selectivity (entries 32–35, Table 4). Again, it should be noted that the reactions of **5k–l** with "I^+" are quite complicated, failing to afford the expected iodides.

When the 1-aryl group was replaced with an alkyl group, i.e., a methyl group, a 2-halo-2-alkenyl ketone, i.e., **13q**, was formed as the major product (Scheme 3).



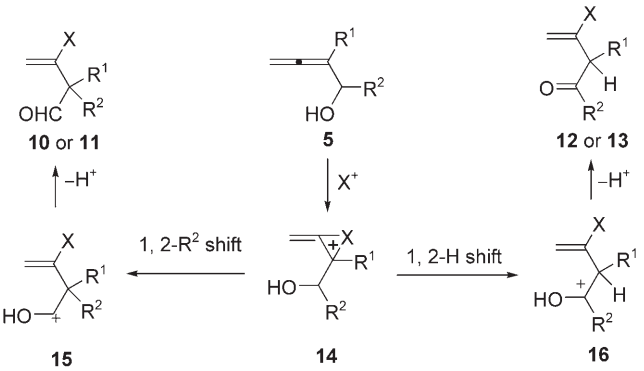
Scheme 3.

Then the reaction was extended to the tertiary 2,3-allenol, i.e., 2-phenyl-3-ethylpenta-3,4-dien-2-ol **5r** affording 4-bromo-4-enone **12r** in 83% yield (Scheme 4).



Scheme 4.

A rationale for this transformation is shown (Scheme 5). The interaction of "X^{+}" with the internal C=C bond of the allene moiety would form intermediate **14**, which would undergo a 1,2-shift of the Ar group to open the three-membered ring forming the cationic homoallylic alcohol intermediate **15**. Upon releasing of H^+ the reaction would form the final 3-halo-3-enals **10** (or **11**). If a 1,2-H transfer occurred, the reaction would form the ketone product **12** (or **13**) *via* the intermediacy of **16**.



Scheme 5.

Conclusions

In summary, it was observed that the reaction of primary 2,3-allenols with I_2 afforded 3-iodo-2,5-dihydrofurans. Under the similar reaction conditions, the reaction of 1-aryl-2,3-allenols afforded 3-halo-3-enals highly selectively when an electron-donating substituent is connected to the aryl group at the 1-position. However, with a relatively electron-withdrawing aryl group or a naphthyl group at the 1-position, a 1,2-H transfer was observed as the minor pathway as well; With an alkyl group group at the 1-position, the 1,2-H shift was observed as the major pathway to afford the 2-halo-2-alkenyl ketones as the major products. Due

to the easy availability of the starting compounds **5** and the not readily available nature as well as the synthetic potential of 3-halo-3-enals or 2-halo-2-alkenyl ketones, this method will be very useful in organic synthesis.[12] Further studies are being carried out in our laboratory.

Experimental Section

General Methods

All the reactions were carried out in the open air unless otherwise indicated. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AM-300 spectrometer or Bruker AM-400 spectrometer. IR spectra were recorded on a Bruker Vector 22 spectrometer. Mass spectra were recorded on a HP 5989 A spectrometer. Flash-column chromatography was carried out on silica gel H (10–40 μ). Petroleum ether with a boiling point range from 60 to 90 °C was used. For the data of compounds reported in the previous communication,[12] see the related supporting information attached to this publication.

Primary 2,3-Allenols

Compounds **2a–i** were prepared according to the known procedure from 2,3-allenoate **1a–i**.[13]

2-Propyldeca-2,3-dien-1-ol (2d); Typical Procedure: DIBAL-H (51.9 mL, 1.0 mol/L solution in toluene, 59.1 mmol) was added dropwise to a solution of 5.88 g (24.7 mmol) of **1d** in 35 mL of anhydrous toluene at −78 °C. After 6.2 h at −78 °C the reaction was complete as monitored by TLC. The mixture was then quenched with 25 mL of methanol and washed with 300 mL of aqueous HCl solution (5%). The organic layer was separated and the aqueous layer was extracted with ether. The combined organic layer was dried over Na_2SO_4, filtered, and evaporated. The residue was purified by column chromatography on silica gel (eluent: petroleum ether/ethyl acetate = 5:1) to give **2d** as an oil; yield: 3.39 g (70%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 5.39–5.30 (m, 1H), 4.07–3.93 (m, 2H), 2.05–1.91 (m, 4H), 1.53–1.21 (m, 11H), 0.93 (t, J = 7.5 Hz, 3H), 0.88 (t, J = 7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 198.7, 105.4, 95.7, 63.0, 31.7, 31.4, 29.3, 28.8, 22.6, 20.9, 14.0, 13.8; IR (neat): ν = 3316, 1964, 1465, 1378, 1156, 1092, 1017 cm^{-1}; MS (70 eV, EI): m/z (%) = 196 (M^+, 0.13), 165 (M^+-CH_2OH, 1.79), 71 (100); elemental analysis: calcd for $C_{13}H_{24}O$ (%): C 79.53, H 12.32; found: C 79.51, H 12.36.

Synthesis of Secondary 2,3-Allenols

Compounds **5a–q** were prepared according to the known procedure[14]

2-Butyl-1-phenylbuta-2,3-dien-1-ol (5a); Typical Procedure: A solution of 1.43 g (8.2 mmol) of **3a**, 2.21 g (11.5 mmol) of $SnCl_2$, and 1.73 g (11.4 mmol) of NaI in 40 mL of DMF was stirred for 1 h at room temperature. Then a solution of 1.16 mL (11.4 mmol) of aldehyde **4a** in 40 mL of DMF was added dropwise at 0 °C. After 12 h at 0 °C as monitored by TLC, the mixture was quenched with 15 mL of water, extracted with diethyl ether, washed with saturated NaCl, and dried over anhydrous Na_2SO_4. Evaporation and column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) afforded **5a**[16] as an oil; yield: 0.66 g (40%); ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.40–7.26 (m, 5H), 5.10 (s, 1H), 5.04–4.96 (m, 2H), 2.21 (bs, 1H), 1.90–1.73 (m, 2H), 1.42–1.32 (m, 2H), 1.32–1.22 (m, 2H), 0.84 (t, J = 7.2 Hz, 3H).

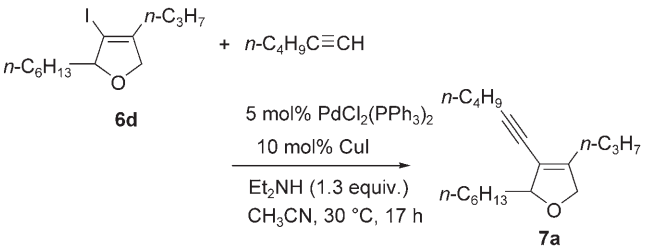
Cyclization of Primary 2,3-Allenols with I_2; General Procedure

A solution of **2** (0.5 mmol) and iodine (1.25 mmol) in 4 mL of MeCN/H_2O (15:1) was stirred at room temperature. When the reaction was complete as monitored by TLC, the mixture was then quenched with 6 mL of water, which was followed by the addition of a saturated aqueous solution of $Na_2S_2O_3$. This mixture was extracted with diethyl ether (3 × 25 mL), washed with an aqueous solution of NaCl, and dried over Na_2SO_4. Concentration and column chromatography on silica gel (petroleum ether/ethyl acetate = 40:1) afforded **6**.

2-Heptyl-3-iodo-2,5-dihydrofuran (6a): The reaction of 85.7 mg (0.5 mmol) of **2a** and 319.5 mg (1.25 mmol) of I_2 in 4 mL of MeCN and 0.27 mL of H_2O at rt for 80 min afforded **6a** as an oil; yield: 97.5 mg (65%); ^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.21 (d, J = 1.6 Hz, 1H), 4.72–4.64 (m, 1H), 4.60–4.50 (m, 2H), 1.80–1.71 (m, 1H), 1.56–1.44 (m, 1H), 1.40–1.21 (m, 10H), 0.87 (t, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 134.8, 92.1, 89.8, 76.2, 33.8, 31.8, 29.5, 29.2, 24.1, 22.6, 14.1. IR (neat): ν = 1612, 1464, 1345, 1237, 1068, 1008 cm^{-1}; MS (70 ev, EI): m/z (%) = 294 (M^+, 2.73), 195 (100); HR-MS: m/z = 294.0479, calcd. for $C_{11}H_{19}IO$ (M^+): 294.0481.

Coupling Reactions of 3-Iododihydrofuran 6d

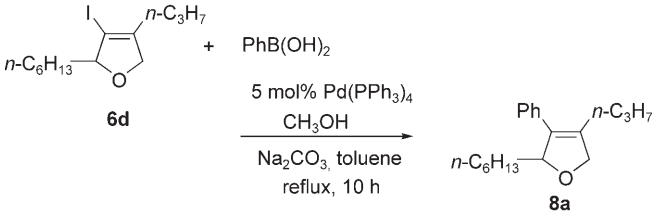
Sonogashira Coupling of 6d with 1-Hexyne to Afford 2-Hexyl-3-hexynyl-4-propyl-2,5-dihydrofuran (7a)



A mixture of 82.0 mg (0.25 mmol) of **6d**, 26.9 mg (0.325 mmol) of 1-hexyne, 24.7 mg (0.325 mmol) of Et_2NH, 4.0 mg (10 mol%) of CuI, and 8.5 mg (5 mol%) of $PdCl_2(PPh_3)_2$ in 2 mL of CH_3CN was stirred at 30 °C under N_2 for 17 h (monitored by TLC, petroleum ether/ethyl acetate = 40:1). Water (6 mL) was added and the reaction mixture was extracted with ether. The combined extract was washed with saturated brine. After drying over Na_2SO_4, filtration, and evaporation, the residue was purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 100:1) to afford **7a** as an oil; yield: 67.3 mg (96%); ^{1}H NMR (400 MHz, $CDCl_3$): δ = 4.74–4.68 (m, 1H), 4.59–4.50 (m, 2H), 2.36 (t, J = 6.8, 2H), 2.25–2.20 (m, 2H), 1.75–1.67 (m,

1H), 1.56–1.20 (m, 15H), 0.94–0.85 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ=143.9, 119.1, 96.1, 87.7, 76.5, 73.3, 34.9, 31.8, 30.9, 29.4, 28.8, 24.6, 22.6, 21.8, 21.0, 19.2, 14.1, 13.9, 13.5; IR (neat): ν=2221, 1653, 1464, 1432, 1379, 1258, 1061 cm^{-1}; MS (70 eV, EI): *m/z* (%)=276 (M^+, 10.67), 191 (100); HR-MS: *m/z*=276.2443; calcd. for $C_{19}H_{32}O$: 276.2453.

Suzuki Coupling of 6d with Phenylboronic Acid to Afford 2-Hexyl-3-phenyl-4-propyl-2,5-dihydrofuran (8a)

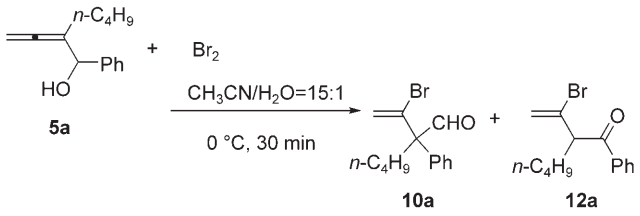


The mixture of 82.5 mg (0.25 mmol) of **6d**, 62.0 mg (0.5 mmol) of phenylboronic acid, 15.5 mg (5 mol%) of $Pd(PPh_3)_4$, 0.1 mL of CH_3OH, and 0.3 mL (2 M in H_2O) of Na_2CO_3 in 2 mL of toluene was refluxed under N_2 for 10 h as monitored by TLC (petroleum ether/ethyl acetate=40:1). Water (6 mL) was added and the reaction mixture was extracted with ether. The combined extract was washed with saturated NaCl. After drying over Na_2SO_4, filtration, and evaporation, the residue was purified by column chromatography on silica gel to afford **8a** as an oil; yield: 64.2 mg (92%); ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.29 (t, J=7.2 Hz, 2H), 7.22–7.19 (m, 1H), 7.12 (d, J=8.0 Hz, 2H), 5.20–5.14 (m, 1H), 4.72 (dd, J_1=12.4, J_2=5.6 Hz, 1H), 4.64 (dd, J_1=12.4, J_2=2.8 Hz, 1H), 2.20–2.09 (m, 2H), 1.49–1.14 (m, 12H), 0.83 (t, J=7.2 Hz, 3H), 0.77 (t, J=7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ=135.05, 134.95, 134.8, 128.3, 128.2, 126.9, 88.8, 77.6, 34.6, 31.8, 29.3, 27.9, 24.7, 22.5, 21.5, 14.1, 14.0; IR (neat): ν=1719, 1597, 1490, 1464, 1378, 1065 cm^{-1}; MS (70 eV, EI): *m/z* (%)=272 (M^+, 9.67), 271 (M^+−H, 36.37), 187 (100); HR-MS: *m/z*=272.2144, calcd. for $C_{19}H_{28}O$: 272.2135.

Reaction of Secondary 2,3-Allenols (5) with X_2 (or NXS)

3-Bromo-2-butyl-2-phenyl-3-butenal (10a); Typical Procedure

To a solution of 82.4 mg (0.41 mmol) of **5a** in 2.4 mL of MeCN and 0.27 mL of H_2O was added with stirring 1.6 mL (0.5 M in MeCN, 0.8 mmol) of Br_2 at 0 °C for 30 min. After complete consumption of the allenol as monitored by TLC, the mixture was quenched with 6 mL of water followed by the addition of a saturated aqueous solution of $Na_2S_2O_3$, extracted with diethyl ether (25 mL×3), washed with NaCl, and dried over anhydrous Na_2SO_4. Evaporation and column chromatography on silica gel (petroleum ether/ethyl acetate=100:1) afforded a mixture of **10a**[12] and **12a**; yield: 91.2 mg (80%) (**10a**:**12a**≥95:5, determined by ^{1}H NMR).



The following data are discernible for **12a**: ^{1}H NMR: δ=5.78 (d, J=2.2 Hz, 1H), 5.63 (d, J=2.2 Hz, 1H).

3-Bromo-2-butyl-2-(1-naphthyl)-3-butenal (10k)

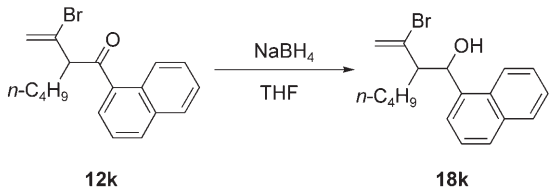
The reaction of 100.2 mg (0.4 mmol) of **5k** and 1.6 mL (0.5 M in MeCN, 0.8 mmol) of Br_2 in 2.4 mL of MeCN and 0.27 mL of H_2O at 0 °C for 30 min afforded a mixture of **10k** and **12k** (90:10); yield: 108.1 mg (73%).

10k: oil, ^{1}H NMR (300 MHz, $CDCl_3$): δ=9.86 (s, 1H), 8.15–8.09 (m, 1H), 7.95–7.83 (m, 2H), 7.55–7.41 (m, 4H), 6.26 (s, 1H), 6.04–5.95 (m, 1H), 2.55–2.41 (m, 1H), 2.35–2.20 (m, 1H), 1.50–1.23 (m, 3H), 0.89 (t, J=6.9 Hz, 4H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=197.1, 134.5, 134.1, 133.3, 131.5, 129.5, 129.3, 126.5, 126.1, 125.7, 125.0, 124.9, 122.4, 64.9, 33.0, 27.1, 23.0, 13.9; IR (KBr): ν=3050, 2957, 2714, 1731, 1599, 1510, 1466, 1397, 1343, 1095, 1025 cm^{-1}; MS (70 eV, EI): *m/z* (%)=332 [M^+ (^{81}Br), 0.22], 330 [M^+ (^{79}Br), 0.23], 303 [M^+ (^{81}Br)−CHO, 5.24], 301 [M^+ (^{79}Br)−CHO, 4.93], 165 (100); HR-MS (EI): *m/z*=330.0626, calcd. for $C_{18}H_{19}{}^{79}BrO$: 330.0619.

The following data are discernible for **12k**: ^{1}H NMR: δ=5.82 (d, J=2.2 Hz, 1H), 5.62 (d, J=2.2 Hz, 1H).

The reaction of 75.5 mg (0.3 mmol) of **5k** and 64.2 mg (0.36 mmol) of NBS in 4 mL of MeCN and 0.27 mL of H_2O at 0 °C for 50 min afforded a mixture of **10k** and **12k** (93:7); yield: 75.8 mg (76%).

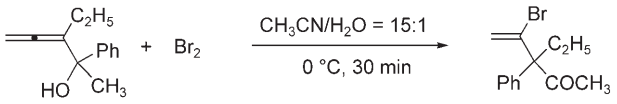
Reduction of Crude 3-Bromo-2-butyl-1-(1-naphthyl)-3-buten-1-one (12k) with $NaBH_4$; Synthesis of 3-Bromo-2-butyl-1-(1-naphthyl)-3-buten-1-ol (18k)



A solution of 38.3 mg of crude **12k** obtained from chromatographic separation and 3.5 mg (0.092 mmol) of $NaBH_4$ in 3 mL of THF was stirred at room temperature for 26 h (monitored by TLC, petroleum ether/ethyl acetate=5:1). The mixture was then quenched with 2 mL of water followed by extraction with diethyl ether (3×10 mL), washed with saturated brine, and dried over anhydrous Na_2SO_4. Evaporation and column chromatography on silica gel (petroleum ether/ethyl acetate=20:1) afforded **18k** as an oil;

yield: 26.5 mg (90%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.29 (d, J = 8.1 Hz, 1H), 7.89 (d, J = 8.4 Hz, 1H), 7.82 (d, J = 8.1 Hz, 1H), 7.61 (d, J = 7.2 Hz, 1H), 7.56–7.43 (m, 3H), 5.91 (s, 1H), 5.75 (s, 1H), 5.36 (d, J = 9.3 Hz, 1H), 2.86–2.74 (m, 1H), 2.28 (d, J = 1.8 Hz, 1H), 1.49–1.32 (m, 1H), 1.23–0.84 (m, 4H), 0.82–0.73 (m, 1H), 0.70 (t, J = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 137.3, 136.7, 133.9, 131.5, 128.9, 128.6, 126.1, 125.6, 125.3, 123.8, 120.8, 77.4, 72.7, 57.3, 29.0, 28.9, 22.1, 13.8; IR (KBr): ν = 3446, 3048, 2955, 2858, 1625, 1597, 1511, 1465, 1394, 1378, 1260, 1225, 1166, 1046 cm^{-1}; MS (70 eV, EI): m/z (%) = 334 [M^+ (^{81}Br), 0.13], 332 [M^+ (^{79}Br), 0.12], 317 [M^+ (^{81}Br)−OH, 1.25], 315 [M^+ (^{79}Br)−OH, 1.15], 157 (100); elemental analysis: calcd. for $C_{18}H_{21}BrO$ (%): C 64.87, H 6.35; found: C 64.83, H 6.37.

Reaction of Tertiary 2,3-Allenol (5r) with Br_2; Synthesis of 4-Bromo-3-ethyl-3-phenyl-4-penten-2-one (12r)



5r **12r**

The reaction of 56.4 mg (0.30 mmol) of **5r** and 0.72 mL (0.5 M in MeCN, 0.36 mmol) of Br_2 in 3.3 mL of MeCN and 0.27 mL of H_2O at 0 °C for 30 min afforded **12r** as an oil: yield: 66.2 mg (83%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.41–7.27 (m, 5H), 6.07 (d, J = 2.4 Hz, 1H), 5.94 (d, J = 2.4 Hz, 1H), 2.29 (q, J = 7.2 Hz, 1H), 2.29 (q, J = 7.2 Hz, 1H), 2.10 (s, 3H), 0.91 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 205.0, 138.2, 135.2, 128.6, 128.4, 127.5, 122.4, 68.9, 27.3, 27.2, 9.3; IR (KBr): ν = 2975, 2880, 1713, 1617, 1495, 1438, 1078 cm^{-1}; MS (70 eV, EI): m/z (%) = 268 [M^+ (^{81}Br), 0.05], 266 [M^+ (^{79}Br), 0.05], 239 [M^+ (^{81}Br)−C_2H_5, 2.39], 237 [M^+ (^{79}Br)−C_2H_5, 2.38], 129 (100); HR-MS: m/z = 291.0174, calcd. for $C_{13}H_{15}{}^{81}$BrONa (M^++Na): 291.0184, 289.0192, calcd for $C_{13}H_{15}{}^{79}$BrONa (M^++Na): 289.0204.

Acknowledgements

We gratefully acknowledge the National Natural Science Foundation of China (No. 20572093), Zhejiang Provincial Natural Science Foundation of China (Y 404262), and Cheung Kong Scholar Program for financial support. We thank Mr. Zhichao Ma in our group for reproducing the results presented in entries 4 and 5 of Table 3.

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