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$CeCl_3 \cdot 7H_2O$–NaI catalyzed intramolecular addition reactions of 7-hydroxy-1,3-dienes: a facile approach to hexahydrobenzofurans and tetrahydrofurans

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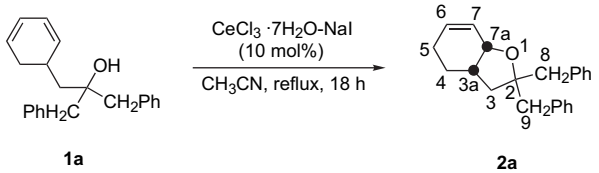
Abstract—$CeCl_3 \cdot 7H_2O$–NaI effectively catalyzed intramolecular cyclization of cyclic 7-hydroxy-1,3-dienes, yielding hexahydrobenzofurans in diastereoselective fashion. This cyclization has been applied to synthesize tetrahydrofurans from acyclic 7-hydroxy-1,3-dienes.

1. Introduction

Condensed heterocycles are widespread in nature, and many of these compounds show interesting biological activities.[1] The benzo[*b*]furan[2] and tetrahydrofuran rings[3,4] are often incorporated in pharmaceutical agents as a core structural motif.[5] Due to the high stereo- and regiochemical control, transition metals such as palladium,[6] molybdenum,[7] and indium[8] have been used to promote the furan-ring formation across unsaturated carbon–carbon bonds and a tethered hydroxyl group. However, many of these catalysts suffer from some drawbacks, which include use of expensive reagents under dry conditions. Therefore, the preparation of benzo[*b*]furan and tetrahydrofuran skeletons is still a challenge for synthetic chemists in order to find safer and milder conditions utilizing more 'friendly' reagents. Recently, cerium(III) chloride has emerged as a very cheap, water-tolerant, and safe reagent and is able to catalyze various selective chemical transformations and cyclizations.[9] In most cases, the activity of $CeCl_3$ can be increased in combination with NaI.[10] The cyclization of unsaturated 3-hydroxy esters to tetrahydrofuranacetic acid esters and tetrahydropyranacetic acid esters catalyzed by $CeCl_3 \cdot 7H_2O$–NaI has been previously reported.[9a] We now report that $CeCl_3 \cdot 7H_2O$–NaI (10 mol %) catalyzes (Scheme 1) intramolecular cyclization of 7-hydroxy-1,3-dienes under mild reaction conditions to afford hexahydrobenzofurans and tetrahydrofurans.



1a **2a**

Scheme 1.

2. Results and discussion

The starting material of 7-hydroxy-1,3-dienes **1a–i** (entries 1–9, Table 1) was prepared by addition of 2.5 equiv of Grignard reagents to the corresponding ester-functionalized 1,3-dienes according to the literature procedures.[11] The primary alcohol **1j** (entry 10, Table 1) was synthesized by addition of $LiAlH_4$ to the corresponding ester at 0 °C in diethyl ether. Secondary alcohol **1k** (entry 11, Table 1) was obtained from addition of $BrZnCH_2CO_2Et$/CuCN to the corresponding aldehyde at −78 °C in THF.[11c]

Our $CeCl_3 \cdot 7H_2O$–NaI catalyzed cyclization study was first carried out by using alcohol **1a**. Treatment of **1a** with 10 mol % equiv of $CeCl_3 \cdot 7H_2O$–NaI in boiling acetonitrile under nitrogen for 18 h afforded, after flash column chromatography, a 58% yield of 2,2-dibenzylhexabenzofuran derivative **2a** as the major product (Scheme 1). The structure for **2a** was established by comparing its ^1H and ^{13}C NMR spectral data with those of related compounds known in the literature.[12] Moreover, the relative stereochemistry of the ring juncture of **2a** was determined as cis on the basis of comparing the coupling constant (4.4 Hz) for hydrogen atoms at C(**3a**) and C(**7a**) to those of related compounds.[12] In order to gain more insights on the intramolecular cyclization of alcohol **1a**, anhydrous $CeCl_3$ (0.1 equiv) and NaI (0.1 equiv) were used. Thus, reaction of **1a** with $CeCl_3$ and NaI in boiling acetonitrile for 18 h produced **2a** in 51% yield. Therefore, water is not needed for the cyclization. However,

Keywords: Cerium chloride; 7-Hydroxy-1,3-diene; Hydroalkoxylation.
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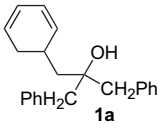
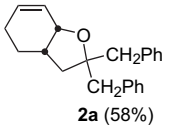
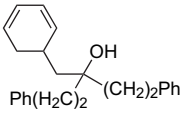
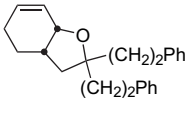
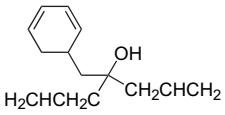
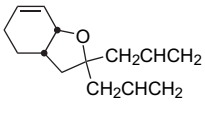
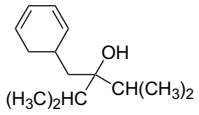
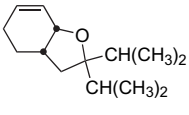
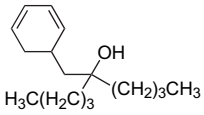
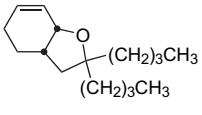
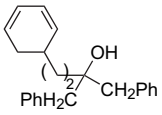
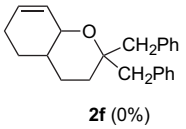
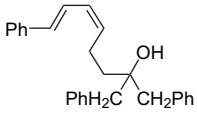
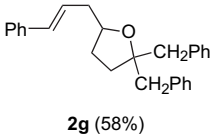
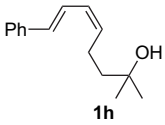
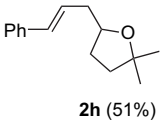
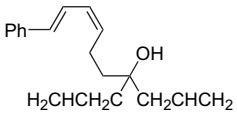
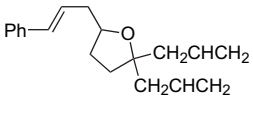
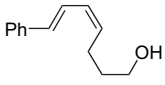
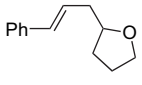
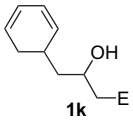
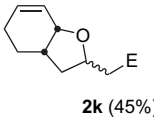
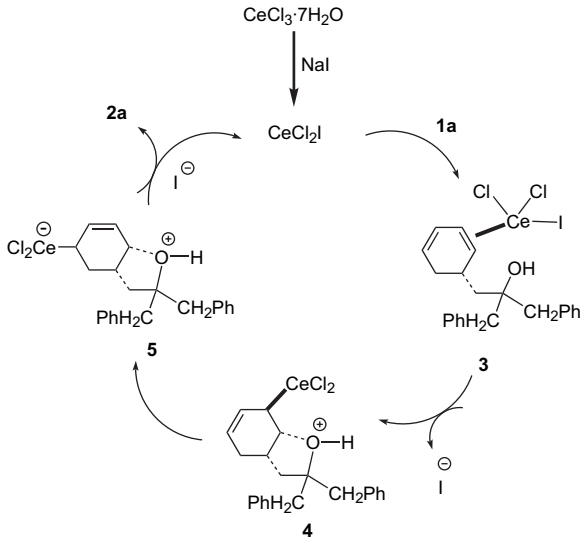
Table 1. Intramolecular addition reactions of 7-hydroxy-1,3-dienes via Scheme 1[a]

Entry	7-Hydroxy-1,3-dienes	Products (yield[b])
1	 **1a**	 **2a** (58%)
2	 **1b**	 **2b** (48%)
3	 **1c**	 **2c** (56%)
4	 **1d**	 **2d** (22%)
5	 **1e**	 **2e** (12%)
6	 **1f**	 **2f** (0%)
7	 **1g**	 **2g** (58%)
8	 **1h**	 **2h** (51%)
9	 **1i**	 **2i** (48%)
10	 **1j**	 **2j** (70%)
11	 **1k**	 **2k** (45%)

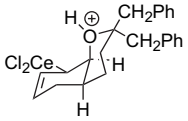
[a] All intramolecular addition reactions were performed in refluxing CH_3CN using 10 mol % of $CeCl_3\cdot 7H_2O$–NaI as the catalyst.
[b] Isolated yields after silica-gel column chromatography.

reaction of **1a** with $CeCl_3\cdot 7H_2O$ alone failed to produce **2a** and alcohol **1a** was recovered almost quantitatively. This is consistent with the failure of cyclization of unsaturated 3-hydroxy esters using $CeCl_3\cdot 7H_2O$ as the sole catalyst reported in the literature.[9a] Based upon the above results, it is reasonable to state that both $CeCl_3$ and NaI are required in the catalytic process. Our proposed reaction mechanism for the $CeCl_3\cdot 7H_2O$–NaI-mediated hydroalkoxylation is shown in Scheme 2. Reaction of $CeCl_3$ with NaI would give $CeCl_2I$. The catalyst $CeCl_2I$ coordinated on the β-face of the proximal double bond of **1a** to give **3**, which was then attacked by the oxygen-nucleophile on the opposite face. This afforded the postulated η^1-allylic intermediate **4** with the newly formed carbon–oxygen bond positioned trans to the cerium–carbon bond. Due to the steric congestion caused by the cerium fragment adjacent to the bicyclic ring juncture, intermediate **4** may undergo η^1–η^3–η^1 allylic rearrangement to the η^1-allylic intermediate **5**. Subsequent protonation of **5** resulted in formation of the 1,4-hydroalkoxylation product **2a** and regeneration of the $CeCl_2I$ catalyst. The addition of an oxygen and a metal across a double bond was found for indium,[8a] palladium,[6b] and cerium[9a] in the literature.



Scheme 2.

Under the same reaction conditions, intramolecular addition reactions of tertiary alcohols **1b–e** using 10 mol % equiv of $CeCl_3\cdot 7H_2O$–NaI in boiling acetonitrile gave hexahydrobenzofurans **2b–e** as single diastereomer in each case (entries 2–5, Table 1). In general, yields of hexahydrobenzofurans are fair (ca. 50%). The fair yields might be due to the fact that $CeCl_3\cdot 7H_2O$–NaI is an efficient reagent for the conversion of tertiary alcohols into alkyl iodides. Moreover, the problem of the competing elimination found in tertiary alcohols reduced the yield of cyclization.[9d] It is important to mention that unlike successful formation of tetrahydrofuran ring, six-membered ring of tetrahydropyran cannot be formed. Thus, intramolecular addition reaction of a substrate with one more methylene unit on the tethered failed and 8-hydroxy-1,3-diene **1f** (entry 6, Table 1) was recovered quantitatively even after refluxing in acetonitrile for 24 h. The failure in the formation of tetrahydropyranyl rings might be attributed to unfavorable formation of the *cis*-decalin intermediate **6**, which contained the bulky cerium fragment adjacent to the bicyclic ring juncture (Chart 1). It is important to mention that cyclization of 3-hydroxy esters

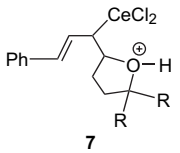


6

Chart 1.

containing a disubstituted olefin using $CeCl_3 \cdot 7H_2O$–NaI as the catalyst led to both terahydro-furanyl and -pyranyl rings.[9a]

Next, the analogous reactions of acyclic 7-hydroxy-1,3-dienes **1g–j** were examined, and the results are listed in entries 7–10, Table 1. Reactions of acyclic substrates **1g–j** with $CeCl_3 \cdot 7H_2O$–NaI (10 mol % equiv) under the same reaction conditions provided the 1,2-hydroalkoxylation products **2g–j** in 48–70% yields. The better yield observed for intramolecular cyclization of the primary alcohol **1j** to give **2j** might be attributed to unfavorable formation of the primary carbocation, which may lead to a primary iodide and/or an olefin via elimination. The 1,2-hydroalkoxylation products **2g–j** apparently derived from protonation of the η^1-allylcerium intermediate **7** (Chart 2). The isolation of 1,2-hydroalkoxylation products from acyclic precursors may suggest that the protonation of Ce–C bond occurred from intermediate **7** at a rate that was faster than η^1–η^3–η^1 allylic rearrangement. The difference in the formation of hydroalkoxylation products (1,4- vs 1,2-hydroalkoxylation) between cylic and acyclic substrates could be explained as follows. The η^1–η^3–η^1 allylic isomerization may be faster in the cyclic intermediate **4** than in the acyclic intermediate **7** for steric reasons. For example, intermediate **7** has more conformational flexibility to minimize unfavorable interactions via the σ-bond (Ce–C) rotation, whereas in **4**, the cerium fragment is close to the bicyclic ring juncture, and the η^1–η^3–η^1 allylic isomerization would place the cerium further away from the tertiary carbon center to give **5**. The η^1-allylcerium intermediate **5** led to 1,4-hydroalkoxylation products **2a–e**. The different reaction paths observed between cyclic and acyclic substrates (1,4- vs 1,2-hydroalkoxylation) were also found for arylalkoxylation of diene alcohols using $Pd(PPh_3)_4$ and aryl bromides in the literature.[12a] It is important to mention that the secondary alcohol **1k** also underwent intramolecular hydroalkoxylation to give **2k** as a mixture of diastereomers in a 1:1 ratio and in 45% total isolated yield (entry 11, Table 1).



7

Chart 2.

3. Conclusion

The reaction outlined herein demonstrates that the $CeCl_3 \cdot 7H_2O$–NaI catalyzed intramolecular addition reaction of an oxygen nucleophile to a conjugated diene can be an effective method for the formation of hexahydrobenzofurans and tetrahydrofurans. With cyclic 7-hydroxy-1,3-dienes, the reaction led to 1,4-hydroalkoxylation products after allylic isomerization of the initial formed η^1-allylcerium intermediate. In contrast to the reactions of cyclic precursors, reactions of acyclic 7-hydroxy-1,3-dienes afforded 1,2-hydroalkoxylation products after protonation of the initial formed η^1-allylcerium intermediate. The use of cerium is economic as compared to catalytic amounts of expensive transition metals employed previously.

4. Experimental

4.1. General methods

All reactions were run using oven-dried glassware under a nitrogen atmosphere unless otherwise indicated. 7-Hydroxy-1,3-dienes **1a–i** were synthesized by addition of 2.5 mol equiv of methyl-, phenyl-, or benzylic magnesium halides to the corresponding esters.[11,12a] The primary dienol **1j** (entry 10, Table 1) was synthesized by addition of $LiAlH_4$ to the corresponding ester at 0 °C in diethyl ether. Secondary dienol **1k** (entry 11, Table 1) was obtained from addition of $BrZnCH_2CO_2Et$/CuCN to the corresponding aldehyde at −78 °C in THF. Anhydrous solvents or reaction mixtures were transferred via an oven-dried syringe or cannula. Tetrahydrofuran (THF) and acetonitrile (CH_3CN) were dried by molecular sieves and then passed through an Al_2O_3 column.[13] Flash column chromatography, following the method of Still, was carried out with E. Merck silica gel (Kieselgel 60, 230–400 mesh) using the indicated solvents.[14] ^1H nuclear magnetic resonance (NMR) spectra were obtained with Bruker-AC 400 (400 MHz) and Bruker-AV 500 (500 MHz) spectrometers. The chemical shifts are reported in parts per million with either tetramethylsilane (0.00 ppm) or $CDCl_3$ (7.26 ppm) as internal standard. ^{13}C NMR spectra were recorded with Bruker-AC 400 (100.4 MHz) spectrometer with $CDCl_3$ (77.0 ppm) as the internal standard. Infrared (IR) spectra were recorded with a JASCO IR-700 spectrometer. Mass spectra were acquired on a JEOL JMS-D 100 spectrometer at an ionization potential of 70 eV and are reported as mass/charge (*m*/*e*) with percent relative abundance. High-resolution mass spectra were obtained with an AEI MS-9 double-focusing mass spectrometer and a JEOL JMS-HX 110 spectrometer at the Department of Chemistry, Central Instrument Center, Taichung, Taiwan.

4.2. General procedure for the intramolecular cyclization of 7-hydroxy-1,3-dienes catalyzed by $CeCl_3 \cdot 7H_2O$–NaI

A mixture of 7-hydroxy-1,3-diene (1.0 mmol), $CeCl_3 \cdot 7H_2O$ (0.1 mmol), and NaI (0.1 mmol) in acetonitrile (10 mL) under nitrogen was stirred at reflux temperature for 18 h (ca. 82 °C). The reaction mixture was extracted with ethyl acetate, and the combined organic layers were washed with H_2O and brine, dried over anhydrous $MgSO_4$, filtered, and the filtrate was concentrated in vacuo. The residue was purified by flash chromatography (silica gel, hexanes/ethyl acetate).

4.2.1. (3a*S,7a*R**)-2,2-Dibenzyl-2,3,3a,4,5,7a-hexahydrobenzofuran 2a.** This compound was prepared from

1a (0.29 g, 0.95 mmol): yield 0.17 g (0.55 mmol, 58%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.21 (m, 10H), 5.64 (m, 2H), 4.19 (m, 1H), 2.87 (s, 2H), 2.76 (m, 2H), 1.85 (m, 2H), 1.76 (m, 3H), 1.39 (m, 1H), 1.16 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 138.5, 138.2, 130.9, 130.7, 128.5, 128.0, 127.8, 127.7, 126.0, 126.0, 84.9, 74.7, 47.8, 46.0, 37.3, 36.23, 23.2, 21.5; IR (CH_2Cl_2) 3048, 3029, 2989, 2927, 1602, 1495, 1454, 1374, 1237, 1033 cm^{-1}; MS (20 eV) *m/e* 304.2 (M^+), 213.1, 135.1, 91.0, 79.0, 61.0; HRMS (EI) *m/e* calcd for $C_{22}H_{24}O$ 304.1827. Found 304.1835.

4.2.2. (3a*S,7a*R**)-2,2-Diphenethyl-2,3,3a,4,5,7a-hexahydrobenzofuran 2b.** This compound was prepared from **1b** (0.63 g, 1.9 mmol): yield 0.30 g (0.9 mmol, 48%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.23 (m, 10H), 5.87 (m, 1H), 5.81 (m, 1H), 4.36 (m, 1H), 2.68 (m, 4H), 2.42 (m, 1H), 1.95 (m, 7H), 1.72 (m, 2H), 1.58 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 142.7, 142.6, 129.8, 128.4, 128.3, 128.3, 127.5, 125.7, 83.9, 73.7, 41.9, 40.9, 40.2, 36.7, 31.1, 30.6, 24.4, 22.6; IR (CH_2Cl_2) 3693, 3601, 3039, 2993, 2941, 2863, 2340, 1603, 1495, 1453, 1433 cm^{-1}; MS (EI) *m/e* (%) 332.6 (M^+, 9), 228.4 (16), 227.4 (86), 105.2 (52), 91.2 (100), 79.2 (32); HRMS calcd for $C_{24}H_{28}O$ (M^+) 332.2140. Found 332.2148; Anal. Calcd for $C_{24}H_{28}O$: C, 86.70; H, 8.49. Found C, 86.99; H, 8.56.

4.2.3. (3a*S,7a*R**)-2,2-Diallyl-2,3,3a,4,5,7a-hexahydrobenzofuran 2c.** This compound was prepared from **1c** (0.50 g, 2.65 mmol): yield 0.28 g (1.42 mmol, 56%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.82 (m, 4H), 5.06 (m, 4H), 4.32 (b, 1H), 2.30 (m, 5H), 2.05 (m, 1H), 1.90 (m, 2H), 1.66 (m, 2H), 1.54 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 134.8, 134.6, 129.8, 127.4, 117.6, 117.4, 83.5, 74.0, 45.2, 43.8, 38.8, 36.5, 24.2, 22.6; IR (CH_2Cl_2) 3686, 2928, 2843, 2366, 2333, 1642, 1609 cm^{-1}; MS (20 eV) *m/e* 163.3 (78), 93.2 (18), 91.2 (12), 85.2(15), 80.2 (12), 79.2 (100), 77.2 (18), 69.2 (58); HRMS (EI) *m/e* calcd for $C_{14}H_{20}O$ 204.1514. Found 204.1520.

4.2.4. (3a*S,7a*R**)-2,2-Diisopropyl-2,3,3a,4,5,7a-hexahydrobenzofuran 2d.** This compound was prepared from **1d** (0.86 g, 4.18 mmol): yield 0.19 g (0.9 mmol, 22%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.76 (m, 2H), 4.45(b, 1H), 2.54 (m, 1H), 2.03 (m, 1H), 1.93 (m, 2H), 1.85 (m, 1H), 1.78 (m, 3H), 1.56 (m, 1H), 0.95 (d, J=6.85 Hz, 6H), 0.88 (d, J=6.85 Hz, 3H), 0.85 (d, J=6.90 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 129.0, 128.2, 89.6, 75.4, 36.7, 35.1, 33.4, 32.9, 24.4, 21.3, 18.9, 18.7, 18.3, 18.0; IR (CH_2Cl_2) 3693, 2961, 2935, 2346, 1609, 1469 cm^{-1}; MS (20 eV) *m/e* 166.3 (13), 165.3 (98), 121.2 (12), 87.2 (49), 80.2 (14), 79.2 (63), 77.2 (12), 71.2 (100), 69.2 (20); HRMS (EI) *m/e* calcd for $C_{14}H_{24}O$ 208.1827. Found 208.1818.

4.2.5. (3a*S,7a*R**)-2,2-Dibutyl-2,3,3a,4,5,7a-hexahydrobenzofuran 2e.** This compound was prepared from **1e** (0.33 g, 1.40 mmol): yield 39 mg (0.16 mmol, 12%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.85 (m, 1H), 5.78 (m, 1H), 4.24 (b, 1H), 2.31 (m, 1H), 2.03 (m, 1H), 1.92 (m, 1H), 1.84 (dd, J=12.55, 8.35 Hz, 1H), 1.44 (m, 15H), 0.89 (m, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 129.8, 127.6, 84.4, 73.2, 40.6, 40.0, 38.3, 36.7, 27.0, 26.4, 24.7, 23.4, 23.3, 23.00, 14.1, 14.1; IR (CH_2Cl_2) 3686, 3601, 2954, 2856, 2719, 2359, 1769, 1609, 1589, 1440, 1371 cm^{-1}; MS (20 eV) *m/e* 236.5 (M^+, 1), 180.4 (14), 179.4 (100), 101.3 (40), 85.2 (78), 79.2 (47); HRMS (EI) *m/e* calcd for $C_{16}H_{28}O$ 236.2140. Found 236.2147.

4.2.6. 2,2-Dibenzyl-5-(*trans*-3-phenylallyl)tetrahydrofuran 2g. This compound was prepared from **1g** (0.37 g, 1.0 mmol): yield 0.21 g (0.58 mmol, 58%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.18–7.42 (m, 15H), 6.67 (d, J=16.0 Hz, 1H), 6.24 (dd, J=16.0, 5.7 Hz, 1H), 4.25 (m, 1H), 3.30 (d, J=14.1 Hz, 1H), 2.28 (dd, J=13.9, 12.6 Hz, 2H), 2.6 (d, J=13.8 Hz, 1H), 1.86 (m, 1H), 1.68 (d, J=11.2 Hz, 2H), 1.39 (m, 2H), 1.16 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 138.3, 137.9, 137.2, 131.5, 131.2, 130.5, 129.3, 128.5, 128.1, 127.5, 127.3, 126.4, 126.1, 125.9, 71.0, 46.1, 39.2, 31.7, 30.6, 19.5; IR (CH_2Cl_2) 3691, 3569, 3084, 3053, 2945, 2869, 2410, 1952, 1733, 1601, 1495, 1453, 1424, 1366, 1263, 1192, 1084, 967 cm^{-1}; MS (20 eV) *m/e* 368.2 (M^+, 4) 277.1 (54), 259.1 (30), 157.1 (15), 143.1 (100), 129.0 (32), 128.0 (33), 91.0 (62); HRMS (EI) *m/e* calcd for $C_{27}H_{28}O$ 368.2140. Found 368.2143.

4.2.7. 2,2-Dimethyl-5-(*trans*-3-phenylallyl)tetrahydrofuran 2h. This compound was prepared from **1h** (0.37 g, 1.71 mmol): yield 0.19 g (0.88 mmol, 51%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.18–7.37 (m, 5H), 6.55 (d, J=16.0 Hz, 1H), 6.20 (dd, J=16.0, 6.2 Hz, 1H), 4.22 (m, 1H), 1.27 (s, 6H), 1.29–1.50 (m, 3H), 1.67–1.75 (m, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 137.1, 131.7, 129.8, 128.4, 127.3, 126.4, 72.1, 71.5, 35.9, 31.9, 31.9, 22.00, 19.90; IR (CH_2Cl_2) 3691, 3589, 3073, 2987, 2935, 2306, 1733, 1601, 1493, 1449, 1374, 1277, 1212, 1036, 967 cm^{-1}; MS (20 eV) *m/e* 216.1 (M^+, 85), 198.1 (14), 159.1 (16), 143.1 (31), 133.0 (91), 131.1 (86), 130.1 (69), 129.1 (50), 128.0 (44), 115.0 (49), 111.1 (51), 105.0 (68), 104.0 (100), 91.0 (64), 57.0 (54); HRMS (EI) *m/e* calcd for $C_{15}H_{20}O$ 216.1514. Found 216.1516.

4.2.8. 2,2-Diallyl-5-(*trans*-3-phenylallyl)tetrahydrofuran 2i. This compound was prepared from **1i** (0.27 g, 1.0 mmol): yield 0.13 g (0.48 mmol, 48%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.18–7.37 (m, 5H), 6.54 (d, J=16.0 Hz, 1H), 6.18 (dd, J=16.0, 6.0 Hz, 1H), 5.87 (m, 2H), 5.09 (m, 4H), 4.23 (m, 1H), 2.67 (dd, J=14.4, 6.2 Hz, 1H), 2.27 (d, J=7.9 Hz, 2H), 2.20 (dd, J=14.4, 8.2 Hz, 1H), 1.67–1.76 (m, 2H), 1.31–1.48 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 137.1, 134.2, 133.9, 131.5, 129.5, 128.4, 127.3, 126.4, 117.5, 117.5, 75.2, 70.8, 45.2, 36.0, 31.8, 31.7, 19.3; IR (CH_2Cl_2) 3691, 3568, 3078, 3047, 2939, 2870, 2304, 1733, 1639, 1444, 1279, 1248, 1071, 998, 936 cm^{-1}; MS (20 eV) *m/e* 268.1 (M^+, 5) 227.1 (23), 209.1 (18), 157.1 (15), 143.1 (100), 129.1 (28), 128.0 (35), 120.1 (22), 115.0 (20), 91.0 (27); HRMS (EI) *m/e* calcd for $C_{19}H_{24}O$ 268.1827. Found 268.1826.

4.2.9. 2-(*trans*-3-Phenylallyl)tetrahydrofuran 2j. This compound was prepared from **1j** (0.23 g, 1.22 mmol): yield 0.16 g (0.85 mmol, 70%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.36 (d, J=7.4 Hz, 2H), 7.28 (t, J=7.4 Hz, 2H), 7.20 (t, J=7.4 Hz, 1H), 6.59 (d, J=15.9 Hz, 1H), 6.20 (dd, J=15.9, 5.7 Hz, 1H), 4.05 (dt,

J=11.3, 2.0 Hz, 1H), 3.95 (m, 1H), 3.52 (td, J=11.4, 2.2 Hz, 1H), 1.86 (d, J=10.8 Hz, 1H), 1.70 (d, J=12.2 Hz, 1H), 1.47–1.61 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 136.9, 129.5, 128.3, 127.3, 126.3, 130.7, 77.8, 68.2, 32.1, 25.7, 23.3; IR (CH_2Cl_2) 3028, 2941, 2850, 1951, 1881, 1732, 1600, 1495, 1449, 1373, 1277, 1203, cm^{-1}; MS (70 eV) *m/e* (rel intensity) 188.1 (M^+, 100), 187.1 (17), 131.0 (56), 129.1 (16), 115.0 (21), 104.1 (89), 103.0 (23), 91.0 (26), 77.0 (17), 55.0 (39); HRMS (EI) *m/e* calcd for $C_{13}H_{16}O$ 188.1201. Found 188.1199.

4.2.10. (2,3,3a,4,5,7a-Hexahydrobenzofuran-2-yl)acetic acid ethyl ester 2k. This compound was prepared from **1k** (0.20 g, 0.95 mmol): yield 0.09 g (0.43 mmol, 45%) as colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.96 (m, 1H), 5.81 (m, 1H), 4.47 (m, 1H), 4.27 (m, 1H), 4.15 (q, J=7.1 Hz, 2H), 2.64 (dd, J=15, 6.8 Hz, 1H), 2.45 (dd, J=15.4, 6.5 Hz, 1H), 2.31 (m, 1H), 2.07 (m, 1H), 1.96 (m, 2H), 1.82 (dt, J=15.4, 7.7 Hz, 1H), 1.67 (m, 1H), 1.46 (m, 1H), 1.26 (t, J=7.2 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.2, 131.1, 126.3, 74.0, 73.5, 60.4, 41.4, 37.1, 36.7, 24.0, 23.2, 14.2; IR (CH_2Cl_2) 3058, 3048, 2929, 1730, 1422, 1280, 1249 cm^{-1}; MS (20 eV) *m/e* 210.1 (M^+, 2), 131.1 (33), 96.1 (38), 94.0 (19), 80.1 (88), 79.1 (100), 77 (21); HRMS (EI) *m/e* calcd for $C_{12}H_{18}O_3$ 210.1256. Found 210.1259.

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