Aluminum Chloride–Tetraalkylammonium Halide Complex as a Novel Catalyst in Friedel–Crafts Alkylation. Direct Construction of the Chroman Structure from 1,3-Diene

Makoto Matsui and Hisashi Yamamoto*

School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-01

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Tetrabutylammonium halides were found to accelerate Lewis acid-catalyzed Friedel–Crafts alkylation when trimethylhydroquinone and myrcene were used, followed by cyclization to give the chroman compound predominantly. For tetraalkylammonium salts which have long-chain alkyls and/or bromide, iodide counter anions promote the reaction in less-polar solvents. Phosphonium halides and sulfonium halide were also effective. The tetraoctylammonium bromide–aluminum chloride complex was an effective catalyst for the initial regioselective protonation of 7,11,15-trimethyl-3-methylene-1,6-hexadecadiene to give α-tocopherol in high yield.

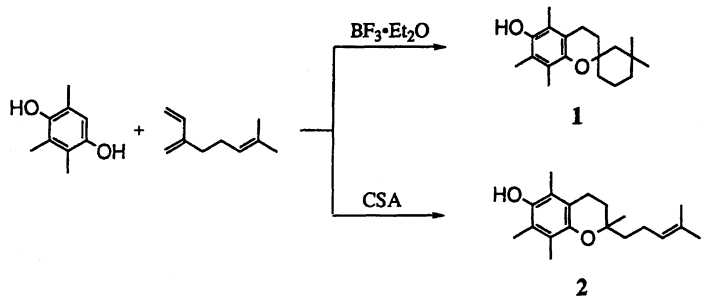
Although Friedel–Crafts alkylation of polyene with hydroquinones is a useful process in the direct construction of the chroman ring structure, few attempts[1)] at this reaction have been made because the initial regioselective protonation of polyene is difficult to achieve. We reported earlier that BF_3·Et_2O produced a spiro compound predominantly, while (+)-10-camphorsulfonic acid (CSA) was an effective catalyst in the regioselective protonation of myrcene to selectively give a chroman compound **2** (Scheme 1).[2)] Protonation by CSA was supposed to occur at the less hindered diene. The selectivity was, however, merely moderate. Recently, the complex derived from aluminum chloride and a phase-transfer catalyst (PTC) was found to increase both the yield and the selectivity in the Friedel–Crafts alkylation of polyene with hydroquinone. Described herein are the results of our attempt to construct the chroman compound using a novel catalyst system consisting of Lewis acid and PTC.

Results and Discussion

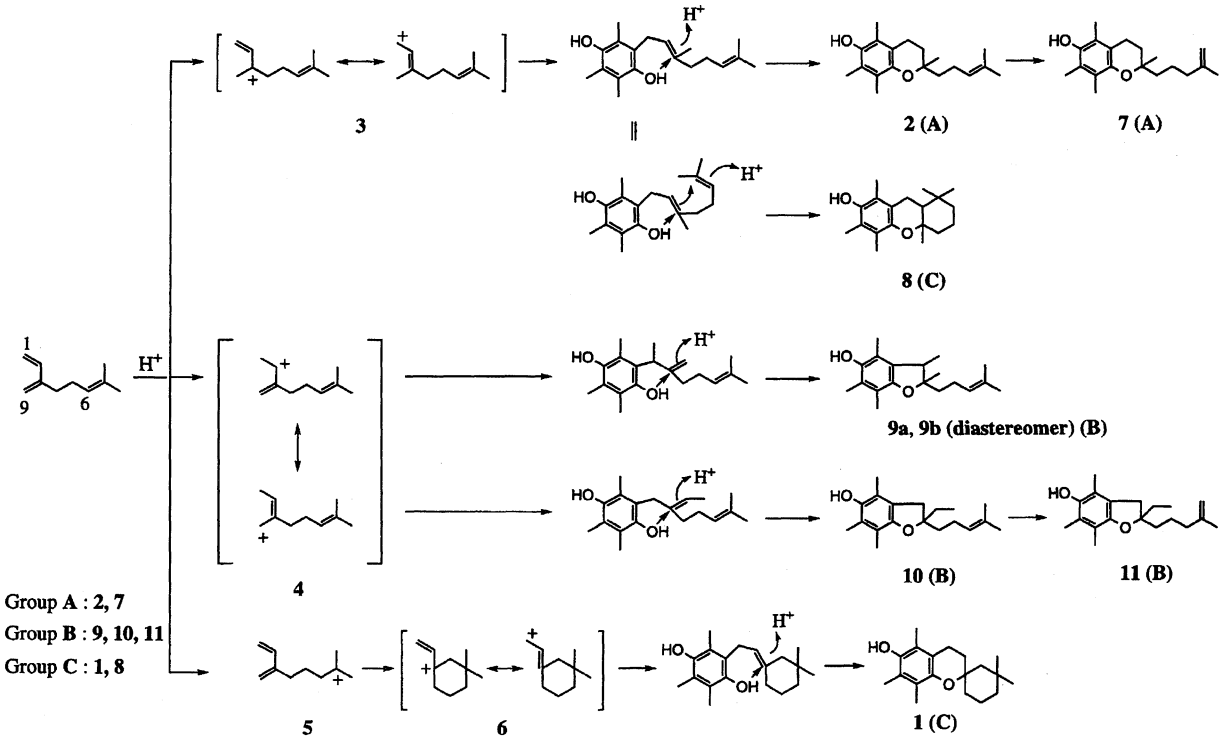
Determination of the Structures for By-products. Aluminum chloride catalyzes the Friedel–Crafts alkylation of hydroquinone with 1,3-diene to give the chroman compound with relatively low selectivity.[1e)] For example, a treatment of aluminum chloride with trimethylhydroquinone and myrcene gave the desired chroman **2** (58% purity, 72% yield) accompanied by several minor products. An elucidation of these minor products was necessary in order to improve the selectivity of the reaction. Although attempts to isolate minor products by the usual silica-gel chromatography failed, ODS separation, which is reversed-phase HPLC, successfully provided six by-products: **7**, **8**, **9a**, **9b**, **10**, and **11**. Four of these were dihydrobenzofuran compounds, **9a**, **9b**, **10**, and **11**, which were supposed to be formed through the reaction of trimethylhydroquinone with the carbenium ion **4**. These by-products might be produced through protonation at the least hindered olefin of myrcene (Scheme 2). The peak of the tricyclic structure **8**, which was apparently produced through further cyclization at the terminal olefin, overlapped with the spiro compound **1** on GLC. These products could be classified as to three groups by the site selectivity of the initial protonation: The initial protonation of myrcene at C_9 produced **2** and **7** (Group **A**); the initial protonation at C_1 afforded **9**, **10**, and **11** (Group **B**). The tricyclic structure **8** might be derived from the initial protonation at C_9 to generate the carbenium ion **3**, followed by further protonation at C_6. The inital protonation at C_6 produced the carbenium ion **5** and, further, **6**, finally to give **1** (Group **C**).

From a mechanistic viewpoint, the initial protonation at C_9 of myrcene should be favorable, due to electronic (production of allylic tertiary cation) and stereochemical reasons (disubstituted olefin). Thus, if the protonation occurs under mild conditions with stereochemically bulky Brønsted acid, we can expect that a higher selectivity of the reaction would be achieved.

Effect of PTC on the Selectivity in the Addition Reaction of Myrcene to Trimethylhydroquinone. Using aluminum chloride, the reaction had proceeded in a suspension. For improving the yield, we added PTC to a mixture of the substrate and Lewis

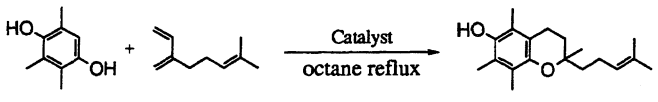


Scheme 1.



Scheme 2.

acid to obtain a homogeneous condition. It was immediately recognized that the use of tetrabutylammonium bromide (TBAB) resulted in a dramatic increase in both the yield and purity of **2** (94% yield, 66% purity) (Scheme 3). Thus, the reactivity and regioselectivity of the Friedel–Crafts reaction in the presence of a variety of PTC were investigated. The results of several quaternary ammonium salts in the reaction of trimethylhydroquinone and myrcene are given in Table 1. The following characteristic features of this reaction are noted: (1) The choice of counter anion of the quarternary ammonium salt was important for higher selectivity and efficiency of the reaction; while F^-, Cl^-, BF_4^-, HSO_4^- ions caused a reduction in the rate of the reaction, Br^- and I^- ions advanced this rate remarkably (Entries 2, 3, 4, 5, 6, and 7). (2) An adequate choice of an alkyl substituent on quarternary ammonium salt is necessary to improve the regioselectivity of the initial protonation. A methyl or ethyl substituent was found to be less effective in the ratio of group-**A** products (Entries 8, and 9). (3) The use of a quaternary ammonium salt bearing a long-chain alkyl substituent resulted in a sat-



$AlCl_3$ (0.2 molar amount) : 72 % yield; 58 % purity
$AlCl_3$ (0.2 molar amount), Bu_4NBr(0.2 molar amount) : 94 % yield; 66 % purity

Scheme 3.

Table 1. Reaction of Trimethylhydroquinone and Myrcene with Aluminium Chloride and Verious PTC[a)]

Entry	Additive	Yield (%)[b)]	A : B : C[c)]
1	None	72	69 : 25 : 6
2	$[Bu_4N^+]F^-\cdot 3H_2O$	<1	
3	$[Bu_4N^+]Cl^-$	43	65 : 16 : 5
4	$[Bu_4N^+]Br^-$	94	78 : 12 : 6
5	$[Bu_4N^+]I^-$	96	79 : 14 : 5
6	$[Bu_4N^+]BF_4^-$	<1	
7	$[Bu_4N^+]HSO_4^-$	20	44 : 15 : 6
8	$[Me_4N^+]Br^-$	35	60 : 20 : 10
9	$[Et_4N^+]Br^-$	54	64 : 15 : 10
10	$[Pr_4N^+]Br^-$	94	75 : 12 : 9
11	$[(C_8H_{17})_4N^+]Br^-$	77	76 : 16 : 2
12	$[Bu_3N^+Bn]Br^-$	79	73 : 12 : 6
13	$[C_{16}H_{33}(C_5H_5N^+)]Br^-$	68	73 : 13 : 6
14	$[C_{16}H_{33}N^+Me_3]Br^-$	84	75 : 15 : 6
15	$[C_{16}H_{33}N^+Me_2Et]Br^-$	98	77 : 14 : 5
16	$[(C_{16}H_{37})_2N^+Me_2]Br^-$	87	77 : 15 : 3
17	$[Me_3N^+(CH_2)_{10}N^+Me_3]I^-{}_2$[d)]	41	67 : 15 : 12
18	$[BuP^+Ph_3]I^-$	99	75 : 14 : 7
19	$[Bu_4P^+]Br^-$	92	74 : 14 : 6
20	$[C_{16}H_{33}P^+Bu_3]Br^-$	82	77 : 15 : 3
21	$[Bu_2S^+Me]I^-$	92	69 : 17 : 11
22	NaI	65	66 : 21 : 9

a) Unless otherwise specified, the reaction was carried out in octane under reflux for 3 h by using trimethylhydroquinone, Lewis acid, quaternary ammonium salt, and myrcene which was added dropwise (1, 0.2, 0.2, 1.1 molar amount respectively). b) Yield of volatile product. c) Determined by GLC analysis. d) 10 mol % of catalyst was used.

isfactory yield and product ratio (Entries 13, 14, 15, and 16). (4) *N,N,N,N′,N′,N′*-Hexamethyl-1,3-decanediaminium iodide, which has two ammonium salts in a molecule, had no effect on the product ratio (Entry 17). (5) Phosphonium salts and a sulfonium salt were also effective catalysts (Entries 18, 19, 20, and 21). (6) The addition of other types of salts, like sodium iodide, had no influence on the product ratio (Entry 22).

Table 2 shows the results of the reaction using various solvents. The reaction proceeded smoothly in a hydrocarbon or ether solvent, while the use of diglyme or 1, 2-diethoxyethane gave only trace amounts of products along with a recovery of the starting trimethylhydroquinone. The donor solvents, valeronitrile and butyl acetate, resulted in a relatively lower yield. The highest regioselectivity (88%) was observed when a solution of trimethylhydroquinone and myrcene in ethyl acetate was added to a suspension of aluminum chloride and tetrabutylammonium iodide in dibutyl ether under reflux (Entry 11).

The combined use of quaternary ammonium halide with other Lewis acids was examined; the results are summarized in Table 3. In every case studied, TBAB increased the ratio of group **A** remarkably. It is noteworthy that the major products were changed by the addition of TBAB. For example, the predominant product was the spiro compound **1** when only $BF_3\cdot Et_2O$ was used. In contrast, when TBAB was added, the generation of **1** decreased to 10% and that of group **A** increased to 62% (Entry 2). Similar results were obtained in the case of $SnCl_4$; two molar amounts of TBAB increased the production of group **A** considerably (Entry 5).

Addition Reaction of 7,11,15-Trimethyl-3-methylene-1,6-hexadecadiene to Trimethylhydroquinone with Quaternary Ammonium Salt–Aluminum Chloride Complex. To demonstrate the applicability of this catalyst system to the synthesis of α-tocopherol, the addition reaction of 7,11,15-trimethyl-3-methylene-1,6-hexadecadiene **12**[4)] to trimethylhydroquinone was examined. A treatment of trimethylhydroquinone and **12** in the presence of tetrabutylammonium iodide–aluminum chloride (0.2 molar amount) under reflux in octane, and subsequent hydrogenation gave α-tocopherol (91% yield, 65% purity) (Scheme 4). Thus, the use of tetraoctylammonium bromide resulted in a satisfactory yield and purity (84% yield, 83% purity).

Although the reason for these striking features in the regioselectivity of the present reaction system is not yet fully understood, it is assumed that aluminum chloride and quaternary ammonium halides form an ate complex, which may be responsible (Eq. 1). In nonpolar solvents, such as octane, the produced ate complex may form a reversed-micelle. The Friedel–Crafts alkylation probably proceeds in that micelle, and as soon as the

Table 2. Reaction of Trimethylhydroquinone and Myrcene with Aluminum Chloride–Tetrabutylammonium Salts in Various Solvents[a)]

Entry	Additive	Solvent	Yield(%)[b)]	**A** : **B** : **C**[c)]
1	$[Bu_4N^+]Br^-$	Benzene	28	26 : 14 : 2
2	$[Bu_4N^+]Br^-$	Toluene	63	66 : 16 : 2
3	$[Bu_4N^+]Br^-$	*o*-Xylene	90	76 : 13 : 2
4	$[Bu_4N^+]Br^-$	Mesitylene	95	79 : 13 : 3
5	$[Bu_4N^+]Br^-$	Heptane	92	72 : 14 : 7
6[d)]	$[Bu_4N^+]Br^-$	Nonane	89	77 : 14 : 5
7	$[Bu_4N^+]Br^-$	Dodecane	90	78 : 14 : 3
8[e)]	$[Bu_4N^+]I^-$	1,1,2,2-Tetrachloroethane	53	64 : 15 : 2
9	$[Bu_4N^+]I^-$	Diisobutyl ether	96	83 : 9 : 4
10	$[Bu_4N^+]I^-$	Dibutyl ether	96	82 : 10 : 3
11[e)]	$[Bu_4N^+]I^-$	Dibutyl ether	84	88 : 8 : 2
12	$[Bu_4N^+]I^-$	Diisopentyl ether	91	82 : 12 : 2
13	$[Bu_4N^+]I^-$	Diglyme	<1	
14[e)]	$[Bu_4N^+]I^-$	1,2-Diethoxyethane	<1	
15[e)]	$[Bu_4N^+]I^-$	Butyl acetate	<1	
16[e)]	$[Bu_4N^+]I^-$	Valeronitrile	41	Not determined

a) Unless otherwise specified, the reaction was carried out in solvent under reflux for 3 h by using trimethylhydroquinone, aluminum chloride, quaternary ammonium salt, and myrcene which was added dropwise (1, 0.2, 0.2, 1.1 molar amount respectively). b) Yield of volatile product. c) Determined by GLC analysis. d) It took 1 h for reaction. e) The reaction was carried out as follow: To a suspension of aluminum chloride and quaternary ammonium in solvent was added a solution of trimethylhydroquinone and myrcene in ethyl acetate under reflux and then this mixture was heated under reflux for 3 h.

Table 3. Reaction of Trimethylhydroquinone and Myrcene with Other Lewis Acid–Tetrabutylammonium Bromide System[a)]

Entry	Catalyst (molar amount)	Yield[b)](%)	**A** : **B** : **C**[c)]
1[d,e)]	$BF_3{\cdot}Et_2O$ (0.2)	86	19 : 2 : 78
2	$BF_3{\cdot}Et_2O$ (0.2), $[Bu_4N^+]Br^-$ (0.2)	44	62 : 10 : 10
3[e)]	$SnCl_4$ (1.0)	99	8 : 8 : 80
4	$SnCl_4$ (0.2), $[Bu_4N^+]Br^-$ (0.2)	72	16 : 8 : 70
5	$SnCl_4$ (0.2), $[Bu_4N^+]Br^-$ (0.4)	55	49 : 12 : 29
6	$Sc(OTf)_3$ (0.2)	90	50 : 12 : 30
7	$Sc(OTf)_3$ (0.2), $[Bu_4N^+]Br^-$ (0.2)	88	63 : 22 : 10
8[f)]	$Y(OTf)_3$ (0.2)	28	44 : 14 : 33
9[g)]	$Y(OTf)_3$ (0.2), $[Bu_4N^+]Br^-$ (0.2)	77	67 : 22 : 2

a) Unless otherwise specified, the reaction was carried out in octane under reflux for 3 h by using trimethylhydroquinone, aluminum chloride, quaternary ammonium salt, and myrcene which was added dropwise. b) Yield of volatile product. c) Determined by GLC analysis. d) It took 0.5 h for reaction. e) *o*-Xylene was used as solvent. f) $Sc(OTf)_3$, $Y(OTf)_3$ were prepared based on the literature.[3)] g) Mesitylene was used as solvent.

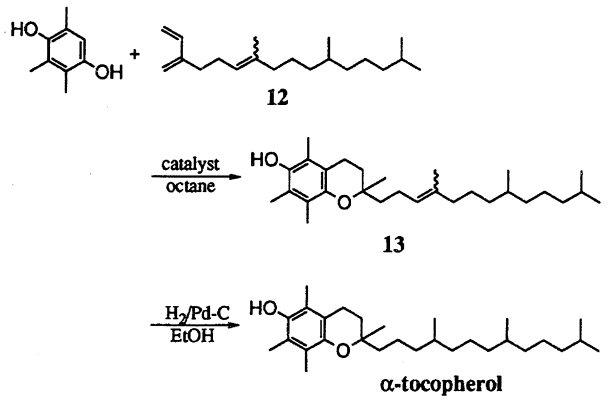
reaction is complete, the product may be extracted to the outside of the micelle, thus preventing the formation of **8**.

$$[R_4N]^+X^- + MX_n \rightleftharpoons [R_4N]^+[MX_{n+1}]^- \quad (1)$$

Conclusion. The addition of tetrabutylammonium halides is effective in a Friedel–Crafts alkylation using hydroquinone and polyene catalyzed by aluminum halide to give the chroman compound as a major product. Tetraalkylammonium halide combined with aluminum halide may form a new class of ate complex. Phosphonium halides and sulfonium halide are as effective as ammonium halide. The onium salts–Lewis acid complex might increase the solubility of the reagent via the assumed reversed micelle system, and, thus, might increase the efficiency and selectivity of the reaction. This novel reagent system may expand the use of Lewis acid catalyst in a nonpolar solvent system, and may be applicable to a wide range of reactions.

Experimental

General. Infrared (IR) spectra were recorded on a Shimadzu FTIR-8100 spectrometer. Analytical gas-liquid-phase chromatography (GLC) was performed on a Gaskuro Kogyo Model 370 instrument with a flame-ionization detector and a capillary column of HP-1(25 m) using nitrogen



Scheme 4.

as the carrier gas. ^{1}H and ^{13}C NMR spectra were measured on Varian Gemini-200 (200 MHz), Gemini-300 (300 MHz), VXR 500S (500 MHz), and JEOL JNM α400 (400 MHz) spectrometer. The chemical shifts of ^{1}H NMR were reported relative to tetramethylsilane (δ=0) or chloroform (δ=7.26). The chemical shifts of ^{13}C NMR were reported relative to $CDCl_3$ (δ=77.00). The splitting patterns are indicated as follows: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; br, broad. The mass spectra were recorded with a Shimadzu QP-5000 mass spectrometer. High-performance liquid chromatography (HPLC) was performed with a Shimadzu LC 6AD instrument using a 20-mm×25-cm JASCO Finepak Sil column. All experiments were carried out under an atmosphere of dry argon. For the thin-layer chromatography (TLC) analyses throughout this work, Merck precoated TLC plates (silica-gel 60 GF_{254}, 0.25 mm) were used. The products were purified by preparative column chromatography on silica-gel E. Merck Art. 9385. Microanalyses were accomplished at the Faculty of Agriculture, Nagoya University.

In experiments requiring dry solvents, benzene, toluene, xylene, and mesitylene, were dried over sodium metal. Other simple chemicals were purchased and used without further purification.

Typical Procedure for the Addition Reaction of Myrcene to Trimethylhydroquinone Using a Lewis Acid and PTC: To a suspension of trimethylhydroquinone (0.20 g, 1.3 mmol) in octane (2.0 ml) was added tetrabutylammonium bromide (85 mg, 0.26 mmol) and aluminum chloride (35 mg, 0.26 mmol); the mixture was then heated under reflux for 5 min. Myrcene (0.26 ml, 95% purity, 1.5 mmol) was first added dropwise to the suspension with refluxing; the mixture was then heated under reflux for 3 h. After cooling, the mixture was poured into saturated aqueous sodium hydrogencarbonate (10 ml) and the product was extracted with diethyl ether (6.0 ml). The combined organic layer was washed twice with saturated aqueous sodium hydrogencarbonate (2×10 ml), and was then washed with brine (10 ml), dried over anhydrous magnesium sulfate and concentrated in vacuo. Nonpolar hydrocarbon and unreacted trimethylhydroquinone in the crude oil was separated by column chromatography on silica-gel (eluent: hexane–AcOEt) to give an addition mixture as a light-brown oil (0.36 g, 94% yield). The **A**:**B**:**C** ratio was determined to be 78:12:6 by a GLC analysis.

Modified Procedure for an Addition Reaction of Myrcene to Trimethylhydroquinone Using Lewis Acid (Table 2, Entries 8, 11, 14, 15 and 16): A mixture of tetrabutylammonium iodide (97 mg, 0.26 mmol) and aluminum chloride (35 mg, 0.26 mmol) in dibutyl ether (2.0 ml) was refluxed for 10 min. To the mixture was added dropwise a solution of trimethylhydroquinone (0.20 g, 1.3 mmol) and myrcene (0.26 ml, 95% purity, 1.5 mmol) in AcOEt (3.0 ml); the mixture was then heated under reflux for 3 h. After cooling, the resultant mixture was poured into saturated aqueous sodium hydrogencarbonate (10 ml), and the product was extracted with diethyl ether (6.0 ml). The combined organic layer was first washed twice with saturated aqueous sodium hydrogencarbonate (2×10 ml), and then with brine (10 ml), dried over anhydrous magnesium sulfate and concentrated in vacuo. Nonpolar hydrocarbon and unreacted trimethylhydroquinone in the crude oil were separated by column chromatography on silica-gel (eluent: hexane–AcOEt) to give an addition mixture as a brown oil (0.32 g, 84% yield). The **A**:**B**:**C** ratio was determined to be 88:8:2 by GLC analysis.

Authentic **1** and **2** were prepared by the literature procedure.[1a,5]

3,4-Dihydro-3′,3′,5,7,8-pentamethylspiro[2*H*-1-benzopyran-2,1′-cyclohexane]-6-ol (1). IR ($CHCl_3$) 3600—3200, 2946, 1456, 1260, 1183, 1086, 1069 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ=0.89 (s, 3H, CH_3), 1.11 (s, 3H, CH_3), 1.15 (d, 1H, J=14.0 Hz, C*H*H), 1.18 (d, 1H, J=15.0 Hz, C*H*H), 1.19 (dd, 1H, J=12.5, 3.5 Hz, C*H*H), 1.43 (m, 1H, C*H*H), 1.47 (br d, 1H, J=12.5 Hz, C*H*H), 1.66 (dt, 1H, J=13.3, 7.0 Hz, C*H*H), 1.68 (br d, 1H, J=14.0 Hz, C*H*H), 1.73 (dt, 1H, J=13.3, 7.0 Hz, C*H*H), 1.80 (m, 1H, C*H*H), 1.85 (br d, 1H, J=15.0 Hz, C*H*H), 2.11 (s, 3H, CH_3), 2.16 (s, 6H, $2CH_3$), 2.60 (t, 2H, J=7.0 Hz, CH_2), 4.19 (s, 1H, OH); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ=11.3, 12.3, 12.5, 18.5, 20.4, 26.8, 30.4, 34.1, 34.3, 34.6, 39.5, 46.9, 73.9, 117.3, 118.5, 121.1, 122.5, 144.4, 145.4; MS (FAB) m/z 288 (M^+), 203, 177, 165, 149, 109, 95. Found: C, 79.01; H, 9.96%. Calcd for $C_{19}H_{28}O_2$: C, 79.13; H, 9.78%.

3,4-Dihydro-2,5,7,8-tetramethyl-2-(4-methyl-3-pentenyl)-2*H*-1-benzopyran-6-ol (2). IR ($CHCl_3$) 4000—3500, 3007, 1456, 1379, 1261, 1225, 1206, 1167, 1086 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ=1.22 (s, 3H, CH_3), 1.54 (m, 2H, CH_2), 1.57 (s, 3H, CH_3), 1.65 (s, 3H, CH_3), 1.77 (m, 2H, CH_2), 2.07 (m, 2H, CH_2), 2.09 (s, 6H, $2CH_3$), 2.14 (s, 3H, CH_3), 2.59 (t, 2H, J=6.8 Hz, CH_2), 4.16 (s, 1H, OH), 5.09 (t, 1H, J=7.2 Hz, CH); MS (EI, 70 eV) m/z 288 (M^+), 203, 191, 177, 165, 152, 136, 121, 69, 43. Found: C, 79.07; H, 9.87%. Calcd for $C_{19}H_{28}O_2$: C, 79.13; H, 9.78%.

The isolation of by products, **7**, **8**, **9a**, **9b**, **10**, and **11**, were performed by HPLC (20-mm×25-cm, JASCO Finepak Sil column). Each by-product contained a small amount of impurities. Spectral data was described below;

7: IR (neat) 3800—3100, 2928, 1508, 1460, 1419, 1375, 1261, 1086, 887 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ=1.23 (s, 3H, CH_3), 1.58 (m, 4H, $2CH_2$), 1.71 (s, 3H, CH_3), 1.78 (dt, 1H, J=13.5, 6.8 Hz, C*H*H), 1.81 (dt, 1H, J=13.5, 6.8 Hz, C*H*H), 2.02 (br, 2H, CH_2), 2.11 (s, 6H, $2CH_3$), 2.16 (s, 3H, CH_3), 2.61 (t, 2H, J=6.8 Hz, CH_2), 4.17 (s, 1H, OH),

4.67 (s, 1H, C*H*H), 4.70 (s, 1H, C*H*H); MS (EI, 70 eV) *m/z* 288 (M^+), 203, 165, 136, 121, 109, 91, 81, 55.

8: IR ($CHCl_3$) 3600, 2937, 1460, 1419, 1379, 1250, 1207, 1105, 1086, 783 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ=0.89 (s, 3H, CH_3), 0.98 (s, 3H, CH_3), 1.10 (s, 3H, CH_3), 1.2—1.7 (m, 6H, $3CH_2$), 1.91 (m, 1H, CH), 2.07 (s, 3H, CH_3), 2.11 (s, 3H, CH_3), 2.13 (s, 3H, CH_3), 2.31 (dd, 1H, J=16.4, 12.8 Hz, C*H*H), 2.59 (dd, 1H, J=16.4, 5.0 Hz, C*H*H), 4.17 (s, 1H, OH); MS (EI, 70 eV) *m/z* 288 (M^+), 217, 203, 165, 136, 109, 91, 69, 55.

9a: IR (neat) 3700—3100, 2926, 1670, 1456, 1415, 1381, 1226, 1080, 1039 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ=1.13 (d, 3H, J=7.1 Hz, CH_3), 1.39 (s, 3H, CH_3), 1.45 (m, 1H, C*H*H), 1.56 (s, 3H, CH_3), 1.63 (s, 3H, CH_3), 1.67 (m, 1H, C*H*H), 2.05 (m, 2H, CH_2), 2.10 (s, 3H, CH_3), 2.12 (s, 3H, CH_3), 2.16 (s, 3H, CH_3), 2.99 (q, 1H, J=7.1 Hz, CH), 4.11 (s, 1H, OH), 5.05 (t, 1H, J=7.2 Hz, CH); MS (EI, 70 eV) *m/z* 288 (M^+), 217, 204, 189, 149, 85, 71, 57.

9b: IR (neat) 3700—3100, 2928, 1674, 1456, 1377, 1230, 1078, 1043, 868 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ=1.10 (d, 3H, J=6.9 Hz, CH_3), 1.26 (s, 3H, CH_3), 1.65 (s, 3H, CH_3), 1.71 (s, 3H, CH_3), 1.87 (m, 2H, CH_2), 2.10 (s, 3H, CH_3), 2.13 (s, 3H, CH_3), 2.17 (s, 3H, CH_3), 2.20 (m, 2H, CH_2), 2.10 (s, 3H, CH_3), 2.97 (q, 1H, J=6.9 Hz, CH), 4.14 (s, 1H, OH), 5.18 (t, 1H, J=6.3 Hz, CH); MS (EI, 70 eV) *m/z* 288 (M^+), 217, 204, 191, 165, 121, 109, 67, 43.

10: IR (neat) 3700—3100, 2926, 1716, 1508, 1458, 1377, 1248, 1084, 910 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ=0.93 (t, 3H, J=7.3 Hz, CH_3), 1.58 (s, 3H, CH_3), 1.67 (s, 3H, CH_3), 1.70 (q, 2H, J=7.3 Hz, CH_2), 1.71 (t, 2H, J=6.8 Hz, CH_2), 2.04 (m, 2H, CH_2), 2.11 (s, 6H, $2CH_3$), 2.13 (s, 3H, CH_3), 2.90 (s, 2H, CH_2), 4.09 (s, 1H, OH), 5.12 (t, 1H, J=7.0 Hz, CH); MS (EI, 70 eV) *m/z* 288 (M^+), 205, 189, 165, 152, 123, 69.

11: IR (neat) 3700—3100, 2926, 1716, 1508, 1460, 1252, 1082, 887 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ=0.92 (t, 3H, J=7.3 Hz, CH_3), 1.50 (m, 2H, CH_2), 1.64 (m, 3H, CH_2), 1.69 (s, 3H, CH_3), 1.70 (m, 2H, CH_2), 2.01 (t, 2H, J=7.3 Hz, CH_2), 2.09 (s, 3H, CH_3), 2.10 (s, 3H, CH_3), 2.12 (s, 3H, CH_3), 2.89 (s, 2H, CH_2), 4.11 (s, 1H, OH), 4.67 (s, 1H, C*H*H), 4.69 (s, 1H, C*H*H); MS (EI, 70 eV) *m/z* 288 (M^+), 217, 205, 189, 165, 123, 85, 71, 57.

Procedure for an Addition Reaction of 7,11,15-Trimethyl-3-methylene-1,6-hexadecadiene to Trimethylhydroquinone Using Tetraoctylammonium Bromide–Aluminum Chloride Complex: To a suspension of trimethylhydroquinone (0.20 g, 1.3 mmol) in octane (2.0 ml) was added tetraoctylammonium bromide (140 mg, 0.26 mmol) and aluminum chloride (35 mg, 0.26 mmol); the mixture was then heated under reflux for 5 min. After 7,11,15-Trimethyl-3-methylene-1,6-hexadecadiene (0.42 g, 95% purity, 1.5 mmol) was added dropwise to the suspension with refluxing, the mixture was heated under reflux for 3 h. Then after cooling, the resulting mixture was poured into saturated aqueous sodium hydrogencarbonate (10 ml) and the product was extracted with EtOAc (6.0 ml). The combined organic layer was first washed twice with saturated aqueous sodium hydrogencarbonate (2×10 ml), and then with brine (10 ml), dried over anhydrous magnesium sulfate and concentrated in vacuo. Hexane (6.0 ml) was added to the crude mixture and the unreacted solid trimethylhydroquinone was filtered out. Nonpolar hydrocarbon and unreacted trimethylhydroquinone in the crude oil were separated by column chromatography on silica-gel (eluent: hexane–EtOAc) to give an addition mixture as a brown oil (0.47 g, 84% yield).

α-Tocopherol. A mixture of the addition products (0.26 g) and 10% Pd/C (50 mg) in ethanol (10 ml) was stirred at room temperature for 14 h under an H_2 atmosphere. The reaction mixture was filtrated, and the catalyst was washed with ether. The organic layer was concentrated in vacuo. The crude oil was purified by column chromatography on silica-gel (eluent: hexane–EtOAc) to give α-tocopherol as a brown oil (0.26 g, 100% yield). The purity was determined to be 83% by a GLC analysis.

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