STUDIES TOWARD THE SYNTHESIS OF PERFORATUMONE:
SYNTHESIS OF THE 7-OXABICYCLO[4.2.1]NONANE-8,9-DIONE CORE

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This paper is dedicated to Professor Tohru Fukuyama on the occasion of his 70th birthday.

Abstract – Construction of the unique bridged bicyclic skeleton, 7-oxabicyclo[4.2.1]nonane-8,9-dione, of perforatumone was achieved. Key steps included a Dieckmann-type condensation, a Claisen rearrangement, and an intramolecular Michael reaction.

More than 100 derivatives of polycyclic polyprenylated acylphloroglucinols (PPAPs) have been isolated from the Guttiferae family of plants and are reported to possess a variety of biological activities.1 PPAPs often contain highly oxygenated, multisubstituted bicyclo[3.3.1]nonane-2,4,9-trione cores. Many chemists have been interested in the structure and biological activity of PPAPs. One of the most widely studied PPAPs is hyperforin (1) (Figure 1), which was isolated from Hypericum perforatum (Saint John’s wort) and is responsible for an antidepressant effect.2 Due to its complex structure, total synthesis of 1 has been challenging for chemists, but the first total synthesis was achieved by Shibasaki, Kanai, and colleagues in 2010.3 Subsequently, several elegant total syntheses of 1 have been reported by Shair and colleagues,4 Uwamori and Nakada,5 Bellavance and Barriault,6 and Ting and Maimone.7

Perforatumone (2) was also isolated from H. perforatum by Harrison and colleagues in 2004.8 The hypothetical biosynthesis indicated that 2 is derived from 1. The structure of 2 was originally reported to include a 7-oxabicyclo[4.2.1]nonane-8,9-dione skeleton, which is a novel structure in nature.9 Total synthesis of 2 has not been achieved, and only two synthetic studies have been reported, by Nicolaou et al.10 and our group.11 However, the structure of perforatumone was recently revised to the congener hyphenrone A (3) by Xu and colleagues.12 Although our targeted structure was consequently wrong, we were interested in the unique bridged bicyclic structure and unknown biological activities of 2. Here, we
describe the synthesis of model compound 4 for the 7-oxabicyclo[4.2.1]nonane-8,9-dione core of 2. Compound 4 could be also converted into the skeleton of 3 through a ring-expansion reaction. Therefore, the development of synthesizing 4 is a worthwhile study for research on PPAPs.

Figure 1. Structures of hyperforin, perforatumone, hyphenrone A, and model compound 4

There are few synthetic studies of the 7-oxabicyclo[4.2.1]nonane-8,9-dione structure and these are based on a ring-expansion reaction. Our synthetic plan for 4 relied on an intramolecular Michael reaction to assemble the bridged bicyclic skeleton. The synthesis of substrate 14 is shown in Scheme 1. Protection of known terminal alkyne 5 with a trimethylsilyl (TMS) group furnished 6 and deprotected alcohol 7. The tert-butyldimethylsilyl (TBS) group of 6 was selectively removed under mild acidic conditions to give more 7. Jones oxidation of 7 provided carboxylic acid 8, which was used for condensation with readily prepared racemic α-hydroxyester 9. Dicyclohexylcarbodiimide (DCC) condensation of 8 and 9 provided diester 10. Dieckmann-type condensation of 10 with lithium bis(trimethylsilyl)amide (LiHMDS) formed a five-membered ring to afford a tetronic acid derivative 11. Subsequent allylation with allyl bromide (LiHMDS/DMF, −60 °C to rt) furnished not only O-allylated product 12, but also C-allylated product 13, with a diastereomeric ratio of 1:1. Using CsF as a base and allyl p-toluenesulfonate (OTs) as an allylation reagent, O-selective allylation and removal of the TMS group proceeded to provide O-allylated product 12 predominantly. Claisen rearrangement of 12 produced C-allyl 13 in high yield with a diastereomeric ratio of 20:1. The stereochemistry of 13 was determined by NOE experiments. The high diastereoselectivity would be useful in the asymmetric synthesis. Desired ynone 14 was obtained by Sonogashira-type coupling of 13 with isobutyryl chloride, accompanied by slight epimerization (diastereomeric ratio = 12:1).

With substrate 14 in hand, we examined the intramolecular Michael reaction. After extensive trial and error, we found that treatment of 14 with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) in N,N-dimethylformamide (DMF) formed the 7-oxabicyclo[4.2.1]nonane-8,9-dione core (Scheme 2).
Cyclized product 4 was obtained as the major isomer in 60% yield along with 11% yield of geometrical isomer 4-Z. The $^1$H and $^{13}$C NMR spectra of 4 showed that it was a single diastereomer, indicating that compound 4 was not a dimerized product because substrate 14 was a racemate; thus, a dimerized product would be a 1:1 diastereomeric mixture. HMBC and NOE experiments also confirmed the structure of 4. Minor isomer 4-Z isomerized to 4 under the same conditions (DBU/DMF, 80 °C) for the Michael reaction, which suggests that the two isomers are reversible, but that 4 is thermodynamically stable.
In conclusion, we have constructed the unique bridged bicyclic skeleton, 7-oxabicyclo[4.2.1]nonane-8,9-dione, of perforatumone (2). The five-membered ring was formed by a Dieckmann-type condensation of diester 10. Claisen rearrangement of O-allyl 12 created a quaternary stereocenter with high diastereoselectivity. The seven-membered ring was constructed by an intramolecular Michael reaction of ynone 14, giving model compound 4. This research provides a new method for constructing a 7-oxabicyclo[4.2.1]nonane-8,9-dione structure.

**EXPERIMENTAL**

**General methods.** $^1$H NMR spectra were recorded at 300 MHz or 400 MHz with tetramethylsilane as an internal standard on a JEOL JNM-LA300 or JEOL JNM-ECS400 spectrometer. $^{13}$C NMR spectra were recorded at 125 MHz on a JEOL JNM-ECA500 spectrometer. High-resolution mass spectra (HRMS) were measured by the ESI mode on a Waters LCT premier XE spectrometer. Thin-layer chromatography (TLC) was performed on Merck Kieselgel 60 F$_{254}$ plates. The crude reaction mixtures and extracted materials were purified by chromatography on Silica gel 60N (Kanto Chemical). Combined organic extracts were dried over anhydrous Na$_2$SO$_4$. Solvents were removed from the reaction mixture and the combined organic extracts by concentration under reduced pressure using an evaporator with bath at 35–45 °C.

7-(tert-Butyldimethylsilyloxy)-3,3-dimethyl-1-(trimethylsilyl)hept-1-yne (6) and 5,5-dimethyl-7-(trimethylsilyl)hept-6-yn-1-ol (7). The following reaction was carried out under Ar. To a cooled (0 °C) stirred solution of 5 (2.50 g, 9.82 mmol) in THF (50 mL) was added $n$-BuLi (2.6 M solution in hexane,
5.3 mL, 14 mmol). The mixture was stirred at 0 °C for 1 h and TMSCl (3.8 mL, 30 mmol) was added. After being stirred at 0 °C for 2 h and at room temperature for 1 h, the mixture was quenched with saturated aqueous NH₄Cl (200 mL) and extracted with EtOAc (100 mL × 3). The combined extracts were washed with saturated brine (300 mL), dried and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:80) to provide 2.15 g (67%) of 6 and 654 mg (31%) of 7. Compound 6 was obtained as a colorless oil: TLC Rf 0.81 (EtOAc/hexane, 1:8); IR (neat) 2958, 2160 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 0.06 (s, 6H), 0.12 (s, 9H), 0.90 (s, 9H), 1.17 (s, 6H), 1.39–1.56 (m, 6H), 3.63 (t, 2H, J = 5.7 Hz); ¹³C NMR (125 MHz, CDCl₃) δ –5.2 (2C), 0.3 (3C), 16.4, 21.6, 26.0 (3C), 29.2 (2C), 31.8, 33.3, 43.1, 63.2, 83.1, 114.9. Compound 7 was obtained as a colorless oil: TLC Rf 0.13 (EtOAc/hexane, 1:8); IR (neat) 3356, 2964, 2158 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 0.13 (s, 9H), 1.18 (s, 6H), 1.36–1.61 (m, 6H), 3.67 (t, 2H, J = 6.6 Hz); ¹³C NMR (125 MHz, CDCl₃) δ 0.3 (3C), 21.4, 29.1 (2C), 31.8, 33.1, 42.9, 62.9, 83.3, 114.7. **Synthesis of 7 from 6.** To a cooled (0 °C) stirred solution of 6 (2.15 g, 6.59 mmol) in THF (21 mL) were added AcOH (64 mL) and H₂O (21 mL). The mixture was stirred at room temperature for 4 h and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:10) to provide 1.41 g (quant) of 7 as a colorless oil.

5,5-Dimethyl-7-(trimethylsilyl)hept-6-ynoic acid (8). To a cooled (0 °C) stirred solution of 7 (2.00 g, 9.42 mmol) in acetone (30 mL) was added Jones reagent (2.67 M CrO₃ in 30 vol% aqueous H₂SO₄, 5.4 mL, 14 mmol). After being stirred at 0 °C for 10 min, the mixture was quenched with 2-propanol (16 mL) and concentrated under reduced pressure. The residue was diluted with H₂O (340 mL) and extracted with EtOAc (170 mL × 5). The combined extracts were washed with saturated brine (340 mL), dried and concentrated under reduced pressure to provide 2.13 g of crude 8, which was used in the next step without further purification.

Methyl 2-[5,5-dimethyl-7-(trimethylsilyl)hept-6-ynoyloxy]pent-4-enoate (10). To a cooled (0 °C) stirred solution of crude 8 (2.13 g) obtained above in CH₂Cl₂ (40 mL) were added a solution of 9 (1.23 g, 9.45 mmol) in CH₂Cl₂ (20 mL), DMAP (115 mg, 0.941 mmol), and DCC (1.94 g, 9.40 mmol). After being stirred at room temperature for 20 h, the mixture was diluted with EtOAc (110 mL), washed with saturated brine (90 mL), dried and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:80) to provide 2.13 g (67% from 7) of 10 as a colorless oil: TLC Rf 0.70 (EtOAc/hexane, 1:3); IR (neat) 2965, 2159, 1745, 1644 cm⁻¹; ¹H NMR (400 MHz, CDCl₃) δ 0.13 (s, 9H), 1.18 (s, 6H), 1.40–1.44 (m, 2H), 1.76–1.84 (m, 2H), 2.43 (t, 2H, J = 7.6 Hz), 2.57–2.65 (m, 2H), 3.74 (s, 3H), 5.09–5.18 (m, 3H), 5.78 (m, 1H); ¹³C NMR (125 MHz, CDCl₃) δ 0.3 (3C), 20.7, 29.1 (2C), 31.6, 34.2, 35.5, 42.4, 52.2, 71.5, 83.6, 114.2, 118.7, 132.0, 170.2, 173.0; HRMS (ESI) calcd for C₁₈H₃₁O₄Si [M+H]⁺ m/z 339.1992, found 339.1987.
3-[3,3-Dimethyl-5-(trimethylsilyl)pent-4-ynyl]-4-hydroxy-5-(2-propenyl)-2(5\text{H})-furanone (11). The following reaction was carried out under Ar. To a cooled (–60 °C) stirred solution of 10 (96.2 mg, 0.284 mmol) in DMF (2 mL) was added LiHMDS (1.0 M solution in THF, 0.50 mL, 0.50 mmol). After being stirred at –60 °C for 20 min, the mixture was quenched with 0.1 M aqueous HCl (10 mL) and extracted with EtOAc/hexane (1:1, 10 mL × 3). The combined extracts were washed with saturated brine (10 mL), dried and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:20) to provide 73.7 mg (85%) of 11 as a reddish oil: TLC \(R_f\) 0.36 (EtOAc/hexane, 1:1); IR (neat) 3340, 2963, 2160, 1747 cm\(^{-1}\); \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 0.15 (s, 9H), 1.21 (s, 6H), 1.55–1.59 (m, 2H), 2.31–2.45 (m, 3H), 2.72 (m, 1H), 4.75 (dd, 1H, \(J = 6.6, 4.3\) Hz), 5.13 (dd, 1H, \(J = 10.4, 1.0\) Hz), 5.18 (dd, 1H, \(J = 17.0, 1.0\) Hz), 5.75 (ddt, 1H, \(J = 17.0, 10.4, 7.0\) Hz), 8.00 (s, 1H, OH); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 0.2 (3C), 17.4, 29.2 (2C), 32.3, 35.6, 40.5, 77.1, 85.0, 102.6, 115.4, 119.4, 130.9, 173.9, 175.5; HRMS (ESI) calcd for C\(_{17}\)H\(_{27}\)O\(_3\)Si \([\text{M+H}]^+\) \(m/z\) 307.1729, found 307.1717.

3-[3,3-Dimethylpent-4-ynyl]-5-(2-propenyl)-4-(2-propenyloxy)-2(5\text{H})-furanone (12). To a cooled (0 °C) stirred solution of 11 (442 mg, 1.44 mmol) in DMF (15 mL) were added CH\(_2\)=CHCH\(_2\)OTs (1.0 mL, 8.7 mmol) and CsF (696 mg, 4.58 mmol). After being stirred at room temperature for 21 h, the mixture was quenched with saturated aqueous NH\(_4\)Cl (15 mL) and extracted with EtOAc/hexane (1:1, 30 mL × 3). The combined extracts were washed with saturated brine (15 mL), dried and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:50) to provide 212 mg (52%) of 12 as a yellow oil: TLC \(R_f\) 0.52 (EtOAc/hexane, 1:3); IR (neat) 3301, 2969, 1753, 1663 cm\(^{-1}\); \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 1.25 (s, 6H), 1.57–1.64 (m, 2H), 2.11 (s, 1H), 2.36 (m, 1H), 2.47–2.55 (m, 2H), 2.69 (m, 1H), 4.68 (dd, 1H, \(J = 6.8, 4.4\) Hz), 4.82 (ddt, 1H, \(J = 12.4, 5.2, 1.2\) Hz), 4.86 (ddt, 1H, \(J = 12.4, 5.2, 1.2\) Hz), 5.14 (dq, 1H, \(J = 10.4, 1.2\) Hz), 5.17 (dq, 1H, \(J = 17.2, 1.2\) Hz), 5.34 (dq, 1H, \(J = 10.4, 1.2\) Hz), 5.40 (dq, 1H, \(J = 17.2, 1.2\) Hz), 5.73 (ddt, 1H, \(J = 17.2, 10.4, 6.8\) Hz), 5.97 (ddt, 1H, \(J = 17.2, 10.4, 5.2\) Hz); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \(\delta\) 19.4, 28.8 (2C), 31.1, 36.0, 42.7, 68.3, 71.7, 76.9, 91.2, 103.1, 118.6, 119.2, 131.0, 131.8, 171.5, 174.3; HRMS (ESI) calcd for C\(_{17}\)H\(_{23}\)O\(_3\) [\text{M+H}]^+ \(m/z\) 275.1647, found 275.1646.

(3\text{S*},5\text{S*})-3-[3,3-Dimethylpent-4-ynyl]-3,5-di(2-propenyl)-2,4(3\text{H},5\text{H})-furandione (13). A solution of 12 (212 mg, 0.773 mmol) and BHT (25.5 mg, 0.102 mmol) in toluene (8 mL) was stirred at 180 °C for 1.5 h in a sealed tube. The mixture was concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:50) to provide 195 mg (92%) of 13 (dr = 20:1) as a colorless oil: TLC \(R_f\) 0.69 (EtOAc/hexane, 1:3); IR (neat) 3298, 2972, 1800, 1755 cm\(^{-1}\); \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 1.18 (s, 6H), 1.23–1.48 (m, 2H), 1.91–2.04 (m, 2H), 2.10 (s, 1H), 2.38–2.58 (m, 3H), 2.66 (m, 1H), 4.61 (dd, 1H, \(J = 8.0, 4.4\) Hz), 5.13–5.25 (m, 4H), 5.66 (m, 1H), 5.81 (m, 1H); \(^{13}\)C NMR
(125 MHz, CDCl$_3$) $\delta$ 28.7 (2C), 29.8, 30.7, 34.6, 37.4, 40.3, 53.8, 68.8, 83.7, 90.0, 120.0, 121.4, 130.0, 130.9, 175.6, 211.7; HRMS (ESI) calcd for C$_{17}$H$_{23}$O$_3$ [M+H]$^+$ m/z 275.1647, found 275.1646.

(3$S^*$,5$S^*$)-3,5-Di(2-propenyl)-3-(3,3,7-trimethyl-6-oxooct-4-ynyl)-2,4(3$H$,5$H$)-furandione (14). The following reaction was carried out under Ar. To a cooled (0 °C) mixture of CuCl (14.8 mg, 0.149 mmol) and Pd(PPh$_3$)$_4$ (164 mg, 0.142 mmol) were added a solution of 13 (195 mg, 0.711 mmol) in toluene (8 mL), Et$_3$N (0.20 mL, 1.4 mmol), and isobutyryl chloride (0.15 mL, 1.4 mmol). After being stirred at 80 °C for 4 h, the mixture was quenched with saturated aqueous NH$_4$Cl (10 mL) and extracted with EtOAc (10 mL x 3). The combined extracts were dried and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:60) to provide 215 mg (88%) of 14 (dr = 12:1) as a colorless oil: TLC $R_f$ 0.58 (EtOAc/hexane, 1:3); IR (neat) 2971, 2206, 1799, 1754, 1672 cm$^{-1}$; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 1.20 (d, 6H, $J$ = 6.9 Hz), 1.24 (s, 6H), 1.27–1.46 (m, 2H), 1.86–1.99 (m, 2H), 2.42–2.56 (m, 3H), 2.58–2.72 (m, 2H), 4.55 (dd, 1H, $J$ = 7.6, 4.6 Hz), 5.15–5.24 (m, 4H), 5.65 (ddt, 1H, $J$ = 16.5, 10.5, 7.1 Hz), 5.87 (ddt, 1H, $J$ = 17.0, 10.1, 7.1 Hz); $^{13}$C NMR (125 MHz, CDCl$_3$) $\delta$ 18.0 (2C), 28.0, 28.2, 29.5, 31.3, 34.5, 37.1, 40.5, 43.1, 53.7, 79.9, 83.7, 99.2, 120.2, 121.5, 129.8, 130.8, 175.4, 192.2, 211.4; HRMS (ESI) calcd for C$_{21}$H$_{29}$O$_4$ [M+H]$^+$ m/z 345.2066, found 345.2053.

(1$S^*$,6$S^*$)-4,4-Dimethyl-5-[(E)-3-methyl-2-oxobutylidene]-1,6-di(2-propenyl)-7-oxabicyclo[4.2.1]-nonane-8,9-dione (4) and (Z)-isomer (4-Z). The following reaction was carried out under Ar. To a cooled (0 °C) stirred solution of 14 (299 mg, 0.869 mmol) in DMF (9 mL) was added DBU (0.19 mL, 1.3 mmol). After being stirred at 80 °C for 7 h, the mixture was quenched with saturated aqueous NH$_4$Cl (9 mL), diluted with H$_2$O (5 mL), and extracted with EtOAc/hexane (1:1, 9 mL x 3). The combined extracts were dried and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:80) to provide 178 mg (60%) of 4 and 32.3 mg (11%) of 4-Z. Compound 4 was obtained as a white amorphous solid: TLC $R_f$ 0.61 (EtOAc/hexane, 1:4); IR (neat) 2931, 1798, 1755, 1698 cm$^{-1}$; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 1.15 (d, 3H, $J$ = 6.8 Hz), 1.16 (d, 3H, $J$ = 6.8 Hz), 1.18 (s, 3H), 1.21 (s, 3H), 1.45 (dt, 1H, $J$ = 15.6, 3.3 Hz), 1.80 (dd, 2H, $J$ = 8.2, 3.3 Hz), 2.08 (dt, 1H, $J$ = 15.6, 8.2 Hz), 2.49 (dd, 1H, $J$ = 14.2, 7.4 Hz), 2.56 (dd, 1H, $J$ = 14.2, 7.4 Hz), 2.71 (sept, 1H, $J$ = 6.8 Hz), 2.79 (d, 2H, $J$ = 7.1 Hz), 5.07–5.23 (m, 4H), 5.59 (ddt, 1H, $J$ = 17.2, 10.1, 7.1 Hz), 5.73 (ddt, 1H, $J$ = 17.2, 10.0, 7.4 Hz), 6.33 (s, 1H); $^{13}$C NMR (125 MHz, CDCl$_3$) $\delta$ 18.2, 18.4, 28.5, 29.7, 31.8, 32.9, 33.9, 39.0, 39.6, 42.0, 57.7, 92.8, 119.7, 122.9, 129.8, 130.7, 131.7, 146.9, 174.3, 208.6, 209.0. Compound 4-Z was obtained as a colorless oil: TLC $R_f$ 0.47 (EtOAc/hexane, 1:4); $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 1.06 (s, 3H), 1.19 (d, 3H, $J$ = 6.7 Hz), 1.20 (d, 3H, $J$ = 6.7 Hz), 1.28 (s, 3H), 1.61 (dt, 1H, $J$ = 15.1, 3.7 Hz), 1.78–1.87 (m, 2H), 2.04 (dt, 1H, $J$ = 15.1, 4.3 Hz), 2.47 (dd, 1H, $J$ = 14.0, 7.1 Hz), 2.54 (dd, 1H, $J$ = 14.0, 7.1 Hz), 2.70 (d, 2H, $J$ = 7.1 Hz), 2.87 (sept, 1H, $J$ = 6.7 Hz), 5.07 (d, 1H, $J$ = 9.9 Hz), 5.10 (d, 1H, $J$ = 17.1 Hz).
Hz), 5.11 (d, 1H, $J = 9.9$ Hz), 5.16 (d, 1H, $J = 17.1$ Hz), 5.43 (ddt, 1H, $J = 17.1, 9.9, 7.1$ Hz), 5.72 (ddt, 1H, $J = 17.1, 9.9, 7.1$ Hz), 6.38 (s, 1H).

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REFERENCES AND NOTES