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Synthesis and stereochemistry of musacins isolated from *Streptomyces griseoviridis* (FH-S 1832)

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Musacins E (**1a**), B_1 (**2a**) and B_2 (**3a**) have been synthesized starting from D-erythronolactone, L-tartaric acid and (*S*)-malic acid. The absolute stereochemistry of musacins was unambiguously established by this synthesis.

Introduction

New secondary metabolites of musacins A to F, which are highly functionalized γ-butyrolactones including a conjugated hydroxy enone, have been isolated[1] from *Streptomyces griseoviridis* (FH-S 1832). The geometry of the double bonds was proposed to be *trans* by spectroscopic analysis; however, the relative and absolute configuration at the four stereogenic centers of musacins B_1 (**2a**) and B_2 (**3a**) was not determined. An analogous butyrolactone, lactone II, closely related to **2a** and **3a** has also been reported.[2] It is reported that the methyl ester (musacin C) of the ring-opened γ-lactone from musacin B_1/B_2 exhibits anthelminthic and weak antiviral activities against adenoviruses, HSV-1 and HSV-2, and the influenza virus. Thus, it is important to clarify the stereostructure for exploring structure–activity relationships among musacins. We describe herein the synthesis and structure of musacins E, B_1 and B_2. Our synthetic plan is briefly illustrated in Fig. 1.

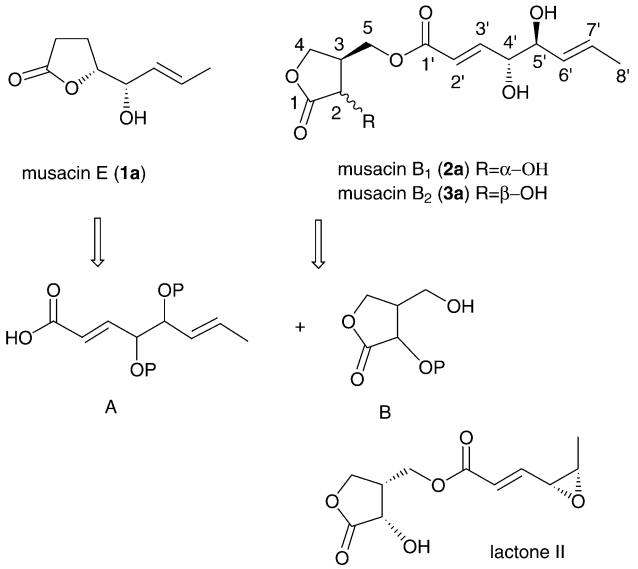

Fig. 1

Results and discussion

Synthesis of the acid unit A

We have assumed that musacin E is the intramolecular ester of the 4,5-dihydroxyocta-6-enoic acid moiety of musacin B_1/B_2, in which esterification takes place with 4-OH to result in a γ-lactone. First, it is necessary to establish the absolute stereochemistry of the dihydroxyl group at the 4,5-position in **1a** (unit A), corresponding to compounds **12a** and **12b**, which were prepared from D-erythronolactone and L-tartaric acid, respectively (Scheme 1).

The requisite acid **13a** (α-series) was synthesized as shown in Scheme 1. The protected ester **5** was obtained from the lactone **4** [prepared from D-erythronolactone] by successive alkaline hydrolysis, silyl protection and esterification with diazomethane. Diisobutylaluminium hydride reduction of **5** afforded the aldehyde **7a** in 92% yield. The Takai reaction[3] of **7a** gave the *trans* olefin **8a** in good yield as a single product. Cyclohexylidene protection was superior to acetonide protection in this coupling reaction. Deprotection of the silyl group in **8a** with tetrabutylammonium fluoride afforded the alcohol **9a**, which was converted to the aldehyde **10a** by the Swern oxidation. The *trans* α,β-unsaturated ester **11a** was obtained in 93% yield as a single product by the Horner–Wadsworth–Emmons reaction.[4] After alkaline hydrolysis of **11a**, the selective reduction of the acid **12a** with sodium borohydride[5] gave **13a** in 87% yield.

Another isomer **13b** (β-series) was synthesized from L-tartaric acid. The alcohol **6** was obtained by the selective silyl protection of the known diol[6] which was derived from L-tartaric acid. The aldehyde **7b** obtained from **6** by the Dess–Martin oxidation was also converted to **13b** by a subsequent series of reactions in the same manner.

Synthesis of 1a

Acid-catalyzed hydrolysis of **13a** and **13b** in hot 1,4-dioxane with concentrated hydrochloric acid gave the γ-lactone **1a** and **1b** in 79 and 68% yield, respectively (Scheme 2). The compound **1a** was found to be identical with the natural product[1] by comparing the optical rotation, MS, ^{1}H and ^{13}C NMR spectra with those reported, while the physical data of **1b** were all different except the MS. Epimerization of the hydroxyl group in **1b** by the Mitsunobu reaction[7] afforded **1c** in 74% yield. Compound **1c** was identical with **1a** in all respects except for the sign of specific optical rotation.

Synthesis of 2a and 3a

Coupling reaction of the acid **12a** with the known lactone **14a**[8] [prepared from (*S*)-malic acid] provided separable compounds **15a** (47%) and **15b** (22%). The stereochemistries of these compound were confirmed by ^{1}H NMR analysis and NOE experiments (Fig. 2). The signals of H-2 appeared at δ 4.48 (J = 8.8 Hz) in **15a** and δ 4.62 (J = 7.9 Hz) in **15b**. A smaller NOE (0.3%) in **15a** and a larger NOE (3.5%) in **15b** were observed. From these results, **15a** and **15b** are presumed to be 2,3-*trans* and 2,3-*cis* isomers, respectively. On treatment of **15a** or **15b** with acetic acid in tetrahydrofuran at 80 °C to remove the cyclohexylidene and tetrahydropyranyl protection, the final products **2a** and **2b** were obtained, respectively, in satisfactory

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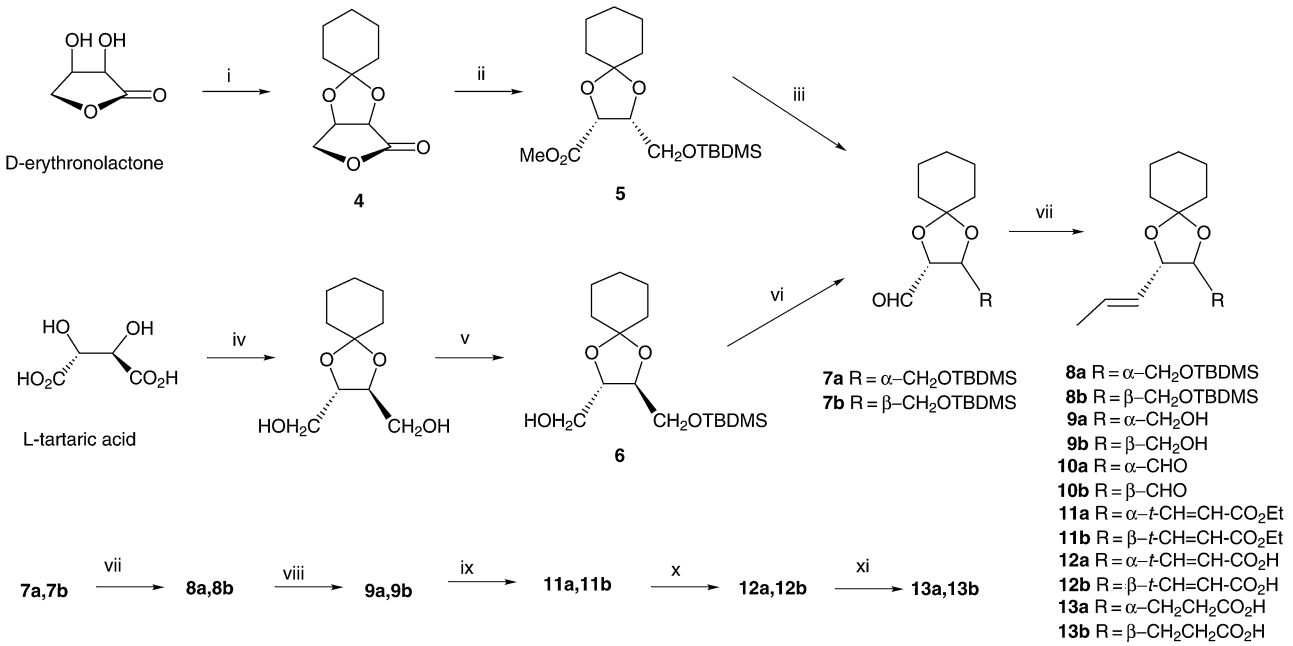
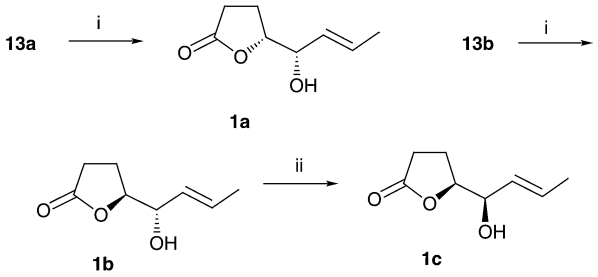


Scheme 1 *Reagents, conditions and yields*: (i) cyclohexanone, *p*-TsOH, toluene, reflux, 80%; (ii) (a) KOH, THF, H_2O, rt; (b) TBDMSCl, DMF, imidazole, rt; (c) diazomethane, ether, 76% (3 steps); (iii) DIBAL, CH_2Cl_2, −78 °C, 92%; (iv) ref. 5; (v) NaH, TBDMSCl, THF, rt, 89%; (vi) Dess–Martin periodinane, CH_2Cl_2, 92%; (vii) $CrCl_2$, CH_3CHI_2, THF, rt, 85%; (viii) TBAF, THF, rt, 100% for **8a**, 97% for **8b**; (ix) (a) $(COCl)_2$, DMSO, Et_3N, CH_2Cl_2, −78 °C; (b) NaH, $(EtO)_2P(O)CH_2CO_2Et$, THF, rt, 93% for **11a**, 91% for **11b** (2 steps); (x) KOH, EtOH, H_2O, rt, 97% for **12a**, 93% for **12b**; (xi) $NaBH_4$, EtOH, 40 °C, 87% for **13a**, 98% for **13b**.



Scheme 2 *Reagents, conditions and yields*: (i) HCl, 1,4-dioxane, 50 °C, 68% for **1a**, 79% for **1a**; (ii) (a) Ph_3P, diethyl azodicarboxylate, benzoic acid, THF, rt, 94%; (b) KOH, EtOH, H_2O, rt, 79%.

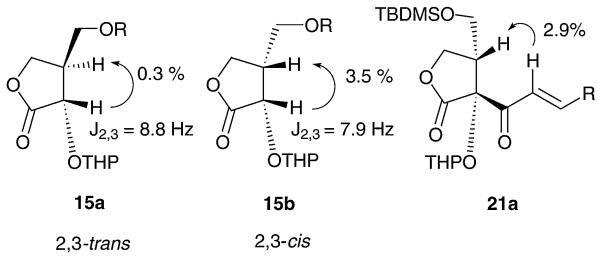


Fig. 2 Coupling constants ($J_{2,3}$) and NOEs of **15a**, **15b** and **21a**.

yield. Isomers **2c** and **2d** were synthesized from **12b** and **14a**, and compounds **3a** and **3b** were also derived from **12a** and **14b**[8] in the same manner. The compounds **2a** and **3b** have similar ^1H and ^{13}C NMR spectra, as do **2b** and **3a**. This is most noticeable in the C2–C3 coupling constants, because they have similar stereochemistry on the lactone ring. Of the twelve compounds (**2a–d**, **3a,b**, **16a–d** and **18a,b**) synthesized as shown in Scheme 3, **2a** and **18a** (the triacetate of **3a**) correspond to the reported compounds, because the NMR and the specific rotations are the closest match (see Experimental section). From these results, the absolute configuration of musacin B_1 (**2a**) and B_2 (**3a**) were determined as 2*S*,3*R*,4′*R*,5′*S* and 2*R*,3*R*,4′*R*,5′*S*, respectively.

Direct synthesis of 2a and 3a by the rearrangement reaction

We have observed[8] the interesting rearrangement *via* intramolecular double esterification of the 3-oxymethyl anion, generated from 2,3-*trans*-3-silyloxymethyl-1′-ketoalkyl-4-butanolides, as shown in Scheme 4. It is assumed that both the compounds **15a** and **17a** are able to be concurrently synthesized from **21** by using this reaction. The key compound **21** was prepared from **11a** by way of four steps (Scheme 5). The alcohol **19** obtained from **11a** by diisobutylaluminium hydride reduction was transformed into the aldehyde **20** by the Dess–Martin oxidation. Alkylation of **20** with the lactone **14c**[8] and subsequent oxidation afforded the ketone **21** in 81% yield. The treatment of **21** with tetrabutylammonium fluoride, as expected, provided **15a** (26%) and **17a** (17%), along with **14a,b** and **13a**. It is probable that the thermodynamically stable *trans* isomer **15a** generated predominantly in the final protonation stage and the low yield of **15a** and **17a** resulted in hydrolysis of the products to give **13a** and **14a,b**.

Conclusion

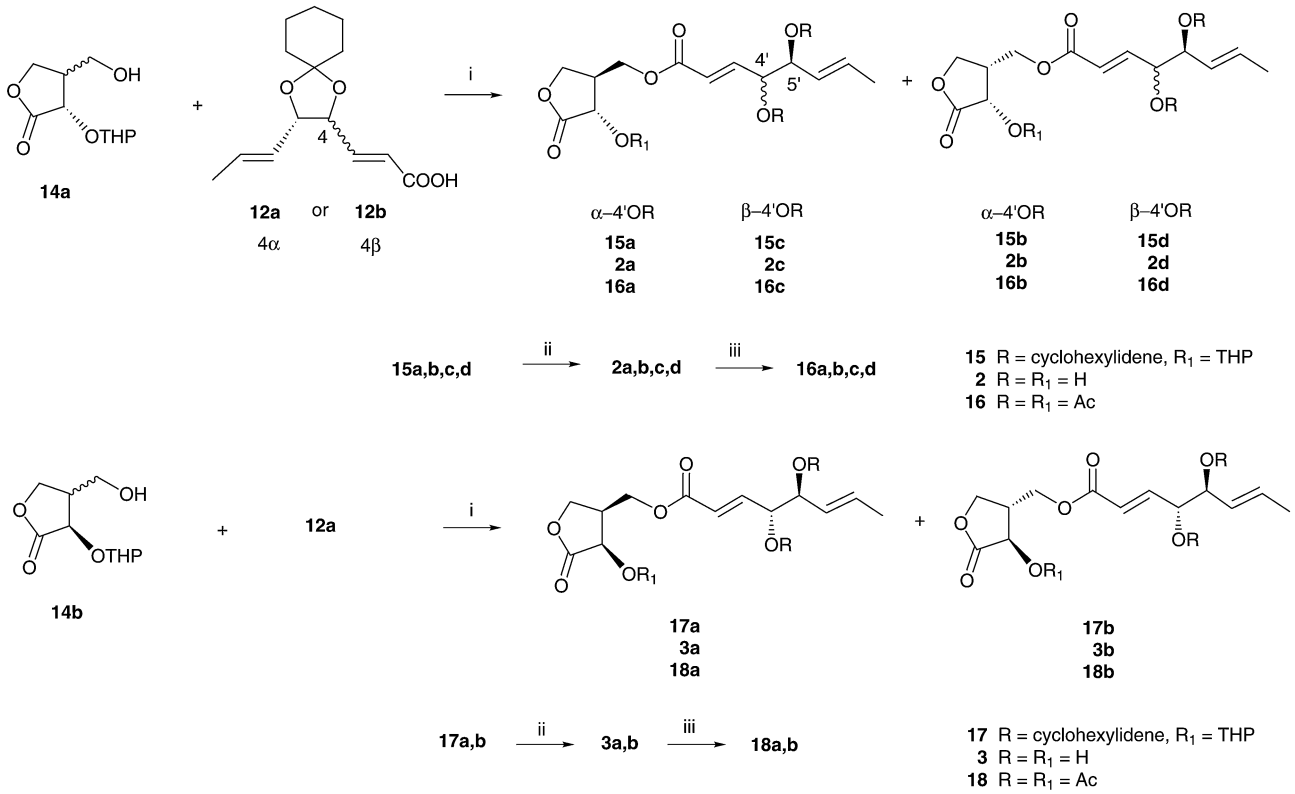
In conclusion, we have achieved the stereoselective synthesis of musacins from D-erythronolactone and (*S*)-malic acid, and determined their absolute configurations. The biological activities of compounds related to musacins are currently under investigation and will be reported in due course.

Experimental

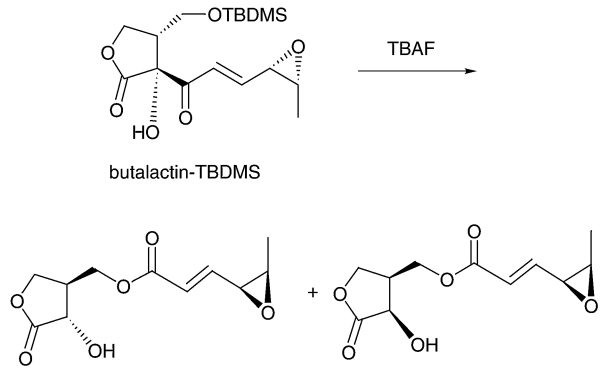
For general experimental procedures see ref. 8.

2,3-*O*-Cyclohexylidene-α-D-erythronolactone 4

A mixture of α-D-erythronolactone (1.0 g, 8.47 mmol), cyclohexanone (1.14 cm^3, 11.0 mmol) and *p*-toluenesulfonic acid (100 mg) in toluene (50 cm^3) was refluxed for 15 h. After cooling the mixture was poured into saturated aqueous $NaHCO_3$, and extracted with ether. The combined organic layers were washed with brine, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 2 : 1) to give **4** (1.35 g,



Scheme 3 *Reagents and conditions*: (i) DCC, DMAP, camphorsulfonic acid, CH_2Cl_2, rt; (ii) AcOH, THF, 80 °C; (iii) Ac_2O, pyridine, rt.

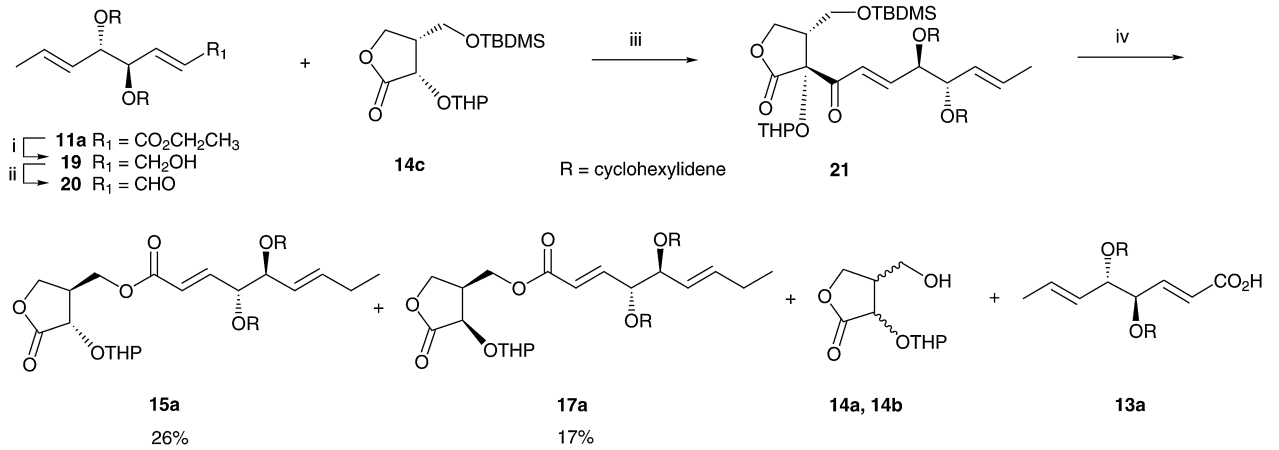


Scheme 4 Intramolecular double esterification of the 3-oxymethyl anion.

80%) as a colorless needles; mp: 79–80 °C (ethyl acetate); $[a]_D^{21}$ −106.6 (*c* 1.03, $CHCl_3$); ν_{max}(nujol)/cm^{-1} 1773, 1456, 1371, 1184, 1113, 1061, 990 and 929; δ_H (300 MHz, $CDCl_3$): 4.87 (1H, dd, *J* 3.7 and 5.7), 4.75 (1H, d, *J* 5.5), 4.48 (1H, d, *J* 11.1), 4.40 (1H, dd, *J* 3.7 and 11.1), 1.57–1.67 (8H, m) and 1.40–1.42 (2H, m); δ_C (75 MHz, $CDCl_3$): 174.2 (s), 114.7 (s), 75.0 (d), 74.3 (d), 70.3 (t), 36.3 (t), 35.0 (t), 24.7 (t), 23.8 (t) and 23.6 (t); [Found: M^+, 198.0895. $C_{10}H_{14}O_4$ requires *M*, 198.0892].

Methyl (2*R*,3*R*)-4-(*tert*-butyldimethylsilyloxy)-2,3-*O*-cyclohexylidenebutanoate 5

To a solution of **4** (527 mg, 2.66 mmol) in THF (5 cm^3) was added 50% aqueous KOH (2 cm^3). After stirring for 45 min at room temperature, the mixture was concentrated to dryness. To the residue in DMF (20 cm^3) was added 4 Å molecular sieves (5 g), imidazole (1.09 g, 16.0 mmol) and *tert*-butyldimethylsilyl chloride (1.2 g, 8.0 mmol), and the mixture was stirred for 45 min



Scheme 5 *Reagents, conditions and yields*: (i) DIBAL, THF, −78 °C, 72%; (ii) Dess–Martin periodinane, CH_2Cl_2, 84%; (iii) (a) LDA, HMPA, THF, −78 °C; (b) Dess–Martin periodinane, CH_2Cl_2, 81% (2 steps); (iv) TBAF, THF, 0 °C.

at room temperature. The reaction mixture was quenched with water and extracted with ether. After acidification (pH 4) of the water layer with 3 M aqueous phosphoric acid, the aqueous layer was extracted with ether. The combined organic layer was washed with water, after esterification with diazomethane, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 5 : 1) to give **5** (699 mg, 76%) as a colorless oil; $[\alpha]_D^{22}$ −2.5 (*c* 0.89 $CHCl_3$); ν_{max}(film)/cm^{-1} 2936, 2857, 1767, 1369, 1253, 1204 and 1107; δ_H (300 MHz, $CDCl_3$): 4.63 (1H, d, *J* 7.1), 4.38 (1H, dt, *J* 5.0 and 7.1), 3.78 (1H, dd, *J* 5.3 and 11.0), 3.73 (3H, s), 3.69 (1H, dd, *J* 4.7 and 11.0), 1.79–1.83 (2H, m), 1.58–1.67 (6H, m), 1.40–1.43 (2H, m), 0.88 (9H, s), 0.06 (3H, s) and 0.05 (s, 3H); δ_C (75 MHz, $CDCl_3$): 170.1 (s), 111.2 (s), 77.9 (d), 74.8 (d), 61.7 (t), 51.9 (q), 36.6 (t), 34.8 (t), 25.8 (q), 25.1 (t), 24.0 (t), 23.7 (t), 18.3 (s), −5.37 (q) and −5.43 (q); [Found: M^+, 344.2043. $C_{17}H_{32}O_5Si$ requires *M*, 344.2019].

(2*S*,3*S*)-4-(*tert*-Butyldimethylsilyloxy)-2,3-*O*-cyclohexylidenebutan-1-ol 6

To a suspension of sodium hydride (60% dispersion in mineral oil; 852 mg, 21.3 mmol) in THF (50 cm^3) was added 2,3-*O*-cyclohexylidene-L-threitol[6] (2.15 g, 10.6 mmol) at 0 °C, and the mixture was stirred for 45 min. *Tert*-butyldimethylsilyl chloride (1.6 g, 10.6 mmol) was added to the mixture, and the reaction mixture was stirred overnight. After quenching with water the mixture was extracted with ether, washed with water, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 8 : 1) to give **6** (2.98 g, 89%) as a colorless oil; $[\alpha]_D^{27}$ +8.4 (*c* 0.86, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 3.98 (1H, t, *J* 7.0), 3.84–3.91 (2H, m), 3.62–3.80 (3H, m), 1.57–1.62 (8H, m), 1.38–1.40 (2H, m), 0.90 (9H, s) and 0.09 (6H, s); δ_C (75 MHz, $CDCl_3$): 109.6 (s), 79.8 (d), 77.7 (d), 63.9 (t), 62.9 (t), 36.6 (t), 36.5 (t), 25.8 (q), 25.1 (t), 23.9 (t), 23.8 (t), 18.3 (s) and −5.5 (q); [Found: M^+, 316.2053. $C_{16}H_{32}O_4Si$ requires *M*, 316.2070].

(2*R*,3*S*,4*E*)-1-(*tert*-Butyldimethylsilyloxy)-2,3-*O*-cyclohexylidene-4-hexene 8a

To a solution of **5** (618 mg, 1.79 mmol) in dichloromethane (16 cm^3) was added diisobutyl aluminium hydride (1.5 *M* in toluene, 1.32 cm^3, 1.98 mmol) at −78 °C, and the mixture was stirred for 1 h. The reaction mixture was quenched by addition of water, and the precipitated inorganic material was removed by filtration through Celite. The filtrate was washed with water, dried and concentrated to give aldehyde **7a**: δ_H (300 MHz, $CDCl_3$): 9.68 (1H, d, *J* 2.2), 4.49 (1H, dd, *J* 2.2 and 6.9), 4.41 (1H, ddd, *J* 2.8, 3.8 and 6.9), 3.80 (1H, dd, *J* 3.8 and 11.3), 3.69 (1H, dd, *J* 2.8 and 11.3), 1.54–1.80 (8H, m), 1.40–1.43 (2H, m), 0.88 (9H, s), 0.05 (3H, s) and 0.04 (3H, s); δ_C (75 MHz, $CDCl_3$): 200.5 (d), 111.3 (s), 80.5 (d), 79.4 (d), 60.6 (t), 36.5 (t), 34.5 (t), 25.7 (q), 25.0 (t), 23.9 (t), 23.7 (t), 18.1 (s), −5.5 (q) and −5.7 (q). This was used without further purification in the following step. To a suspension of chromium(II) chloride (1.33 g, 10.8 mmol) in THF (20 cm^3) under a nitrogen atmosphere in the dark at 0 °C was added a solution of **7a** and 1,1-diiodoethene (0.36 cm^3, 3.59 mmol) in THF (5 cm^3) in one portion. After stirring for 17 h at room temperature, water (20 cm^3) was added and the mixture was extracted with ether. The combined organic phase was washed with saturated aqueous $NaHCO_3$ and brine, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 30 : 1) to give **8a** (496 mg, 85%, 2 steps) as a colorless oil; $[\alpha]_D^{20}$ −1.04 (*c* 0.94, $CHCl_3$); ν_{max}(film)/cm^{-1} 2935, 2857, 1251, 1098 and 967; δ_H (300 MHz, $CDCl_3$): 5.77 (1H, dqd, *J* 1.0, 6.4 and 15.2), 5.51 (1H, qdd, *J* 1.3, 8.3 and 15.2), 4.56 (1H, dd, *J* 6.8 and 7.7), 4.13 (1H, dd, *J* 6.2 and 12.2), 3.63 (1H, dd, *J* 6.3 and 10.4), 3.59 (1H, dd, *J* 5.7 and 10.4), 1.72 (3H, dd, *J* 1.3 and 6.4), 1.57–1.62 (8H, m), 1.35–1.39 (2H, m), 0.88 (9H, s), 0.06 (3H, s) and 0.05 (3H, s); δ_C (75 MHz, $CDCl_3$): 130.1 (d), 126.7 (d), 108.7 (s), 78.3 (d), 78.1 (d), 62.4 (t), 37.8 (t), 34.8 (t), 25.8 (q), 25.2 (t), 24.1 (t), 23.8 (t), 18.2 (s), 17.9 (q), −5.38 (q) and −5.43 (q); [Found: M^+, 326.2251. $C_{18}H_{34}O_3Si$ requires *M*, 326.2277].

(2*S*,3*S*,4*E*)-1-(*tert*-Butyldimethylsilyloxy)-2,3-*O*-cyclohexylidene-4-hexene 8b

Dess–Martin periodinane (1.76 g, 4.14 mmol) was added to a solution of **6** (655 mg, 2.07 mmol) in dichloromethane (40 cm^3). After stirring at room temperature for 2 h, the mixture was diluted with ether and quenched by addition of saturated aqueous $NaHCO_3$ (20 cm^3) and saturated aqueous sodium thiosulfate (20 cm^3). After dissolution of the precipitate that was formed, the mixture was washed with aqueous $NaHCO_3$ and water, dried and evaporated. The residue was purified by chromatography to afford **7b** as a pale yellow oil; δ_H (300 MHz, $CDCl_3$): 9.76 (1H, d, *J* 1.7), 4.31 (1H, dd, *J* 1.7 and 7.0), 4.12 (1H, dt, *J* 4.6 and 7.0), 3.79 (2H, d, *J* 4.4), 1.61–1.62 (8H, m), 1.40–1.43 (2H, m), 0.90 (9H, s) and 0.08 (6H, s); δ_C (75 MHz, $CDCl_3$): 201.1 (d), 112.1 (s), 81.7 (d), 77.2 (d), 63.1 (t), 36.4 (t), 35.8 (t), 25.8 (q), 24.9 (t), 23.8 (t), 23.7 (t), 18.3 (s), −5.4 (q) and −5.5 (q).

The aldehyde **7b** was treated with chromium(II) chloride and 1,1-diiodoethene as described above to give **8b** in 72% yield (2 steps) as a colorless oil; $[\alpha]_D^{29}$ −7.7 (*c* 1.33, $CHCl_3$); ν_{max}(film)/cm^{-1} 2936, 2859, 1448, 1166, 1103, 1045 and 966; δ_H (400 MHz, $CDCl_3$): 5.79 (1H, qd, *J* 6.6 and 15.2), 5.47 (1H, dd, *J* 7.6 and 15.2), 4.25 (1H, t, *J* 7.6), 3.63–3.80 (3H, m), 1.71 (3H, d, *J* 6.6), 1.61–1.63 (8H, m), 1.38–1.40 (2H, m), 0.89 (9H, s) and 0.06 (6H, s); δ_C (100 MHz, $CDCl_3$): 130.7 (d), 128.9 (d), 109.2 (s), 80.9 (d), 78.8 (d), 62.7 (t), 36.7 (t), 36.4 (t), 25.8 (q), 25.2 (t), 23.9 (t), 23.8 (t), 18.3 (s), 17.8 (q), −5.3 (q) and −5.4 (q); [Found: M^+, 326.2268. $C_{18}H_{34}O_3Si$ requires *M*, 326.2277].

(2*R*,3*S*,4*E*)- and (2*S*,3*S*,4*E*)-2,3-*O*-cyclohexylidene-4-hexen-1-ol 9a and 9b

To a solution of **8a** (233 mg, 0.71 mmol) in THF (15 cm^3) was added tetra-*n*-butylammonium fluoride (1.0 M in THF, 2.1 cm^3, 2.1 mmol) at 0 °C, and the mixture was stirred for 1 h at room temperature. The reaction mixture was quenched with aqueous NH_4Cl, and extracted with ether. The extract was washed with water and brine, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 5 : 1) to give **9a** (151 mg, 100%) as a colorless oil; $[\alpha]_D^{20}$ +34.8 (*c* 1.56, $CHCl_3$); ν_{max}(film)/cm^{-1} 3424, 2936, 2859, 1448, 1364, 1283, 1166, 1041 and 971; δ_H (300 MHz, $CDCl_3$): 5.84 (1H, qd, *J* 6.5 and 15.2), 5.51 (1H, qdd, *J* 1.5, 8.2 and 15.2), 4.61 (1H, dd, *J* 7.9 and 8.2), 4.20 (1H, ddd, *J* 5.8, 7.9 and 12.0), 3.58 (2H, br s), 2.04 (1H, br s, OH), 1.74 (3H, dd, *J* 1.5 and 6.5), 1.60–1.64 (8H, m) and 1.39–1.40 (2H, m); δ_C (75 MHz, $CDCl_3$): 131.6 (d), 125.7 (d), 109.1 (s), 77.82 (d), 77.80 (d), 62.2 (t), 37.6 (t), 34.6 (t), 25.1 (t), 23.6 (t) and 17.8 (q); [Found: M^+, 212.1425. $C_{12}H_{20}O_3$ requires *M*, 212.1412].

Compound **9b** was obtained from **8b** in 97% yield as a colorless oil; $[\alpha]_D^{28}$ −19.2 (*c* 0.64, $CHCl_3$); ν_{max}(film)/cm^{-1} 3481, 2936, 2861, 1450, 1365, 1281, 1166, 1105 and 1044; δ_H (400 MHz, $CDCl_3$): 5.84 (1H, qd, *J* 6.4 and 15.4), 5.46 (1H, qdd, *J* 1.3, 8.3 and 15.4), 4.27 (1H, t, *J* 8.3), 3.80–3.85 (1H, m), 3.74–3.78 (1H, m), 3.56 (1H, ddd, *J* 3.7, 8.3 and 12.0), 1.92 (1H, dd, *J* 4.6 and 8.3), 1.73 (3H, dd, *J* 1.3 and 6.6), 1.61–1.68 (8H, m) and 1.38–1.40 (2H, m); δ_C (100 MHz, $CDCl_3$): 131.9 (d), 128.1 (d), 109.4 (s), 80.5 (d), 77.8 (d), 60.8 (t), 36.7 (t), 36.5 (t), 25.1 (t), 23.80 (t), 23.76 (t) and 17.8 (q); [Found: M^+, 212.1387. $C_{12}H_{20}O_3$ requires *M*, 212.1412].

Ethyl (4*R*,5*S*,2*E*,6*E*)- and (4*S*,5*S*,2*E*,6*E*)-4,5-*O*-cyclohexylidene-2,6-octadienoate 11a and 11b

A stirred solution of oxalyl chloride (0.1 cm^3, 1.14 mmol) in dichloromethane (15 cm^3) was cooled to −78 °C, then a solution of DMSO (0.16 cm^3, 2.19 mmol) in dichloromethane (1 cm^3) was added dropwise and stirring was continued for 5 min. Next, a

solution of **9a** (185.6 mg, 0.88 mmol) in dichloromethane (2 cm^3) was added dropwise over 5 min and the resultant slurry stirred for 1 h at −78 °C. After this period, triethylamine (0.61 cm^3, 4.38 mmol) was added and the resultant slurry stirred for an additional 5 min at −78 °C. The mixture was warmed to room temperature over 5 min, and water was added. The mixture was extracted with dichloromethane, washed with water, dried and concentrated to give crude aldehyde **10a** as a pale yellow oil, which was used without further purification in the following step.

Ethyl diethylphosphonoacetate (0.26 cm^3, 1.31 mmol) was added dropwise to a suspension of sodium hydride (60% dispersion in mineral oil; 52.5 mg, 1.31 mmol) in THF (15 cm^3) at 0 °C, and the mixture was allowed to warm to room temperature with stirring for 30 min. The aldehyde **10a** was added to the reaction mixture at 0 °C and stirred for 35 min. After dilution with ether, the mixture was washed with water, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 15 : 1) to give **11a** (227 mg, 93%, 2 steps) as a colorless oil; $[\alpha]_D^{19}$ +27.9 (*c* 1.40, $CHCl_3$); ν_{max}(film)/cm^{-1} 2936, 2857, 1724, 1448, 1367, 1305, 1269, 1165 and 1034; δ_H (300 MHz, $CDCl_3$): 6.81 (1H, dd, *J* 5.3 and 15.6), 6.07 (1H, dd, *J* 1.5 and 15.6), 5.82 (1H, qd, *J* 6.4 and 15.2), 5.35 (1H, qdd, *J* 1.5, 8.0 and 15.2), 4.70 (1H, ddd, *J* 1.5, 6.3 and 7.0), 4.66 (1H, dd, *J* 7.0 and 8.3), 4.21 (2H, q, *J* 7.1), 1.72 (3H, dd, *J* 1.5 and 6.4), 1.60–1.63 (8H, m), 1.41–1.43 (2H, m) and 1.30 (3H, t, *J* 7.1); δ_C (75 MHz, $CDCl_3$): 166.1 (s), 144.4 (d), 131.9 (d), 126.3 (d), 122.4 (d), 109.8 (s), 79.3 (d), 71.1 (d), 60.4 (t), 37.6 (t), 34.8 (t), 25.1 (t), 24.0 (t), 23.7 (t), 17.8 (q) and 14.2 (q); [Found: M^+, 280.1677. $C_{16}H_{24}O_4$ requires *M*, 280.1675].

Compound **11b** was obtained from **9b** in 91% yield as a pale yellow oil; $[\alpha]_D^{30}$ −17.1 (*c* 0.92, $CHCl_3$); δ_H (400 MHz, $CDCl_3$): 6.85 (1H, dd, *J* 5.1 and 15.6), 6.12 (1H, dd, *J* 1.5 and 15.6), 5.84 (1H, qd, *J* 6.6 and 15.4), 5.47 (1H, qdd, *J* 1.5, 8.0 and 15.4), 4.21 (2H, q, *J* 7.1), 4.19–4.23 (1H, m), 4.09 (1H, t, *J* 8.2), 1.74 (3H, dd, *J* 1.5 and 6.6), 1.61–1.69 (8H, m), 1.39–1.41 (2H, m) and 1.30 (3H, t, *J* 7.1); δ_C (100 MHz, $CDCl_3$): 166.0 (s), 143.4 (d), 132.4 (d), 126.7 (d), 122.4 (d), 110.1 (s), 81.6 (d), 79.5 (d), 60.5 (t), 36.6 (t), 36.2 (t), 25.0 (t), 23.8 (t), 23.7 (t), 17.8 (q) and 14.2 (q); [Found: M^+, 280.1681. $C_{16}H_{24}O_4$ requires *M*, 280.1675].

(4*R*,5*S*,2*E*,6*E*)- and (4*S*,5*S*,2*E*,6*E*)-4,5-*O*-cyclohexylidene-2,6-octadienoic acid 12a and 12b

To a solution of **11a** (38.1 mg, 0.14 mmol) in ethanol (3 cm^3) was added 50% aqueous KOH (0.04 cm^3), and the mixture was stirred for 45 min at room temperature. After removal of ethanol, water was added and acidified (pH 4) with 3 M aqueous phosphoric acid. The aqueous solution was extracted with ether, and the extract was dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 2 : 1) to give **12a** (33.4 mg, 97%) as a white wax; $[\alpha]_D^{20}$ +33.1 (*c* 1.43, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 6.92 (1H, dd, *J* 5.1 and 15.6), 6.09 (1H, dd, *J* 1.5 and 15.6), 5.83 (1H, qd, *J* 6.6 and 15.0), 5.33 (1H, qdd, *J* 1.7 Hz, 8.2 and 15.0), 4.74 (1H, ddd, *J* 1.5, 5.1 and 6.8), 4.68 (1H, dd, *J* 6.8 and 8.2), 1.72 (3H, dd, *J* 1.7 and 6.6), 1.59–1.69 (8H, m) and 1.41–1.43 (2H, m); δ_C (75 MHz, $CDCl_3$): 171.3 (s), 147.2 (d), 132.0 (d), 126.1 (d), 121.6 (d), 110.0 (s), 79.3 (d), 76.9 (d), 37.5 (t), 34.7 (t), 25.0 (t), 24.0 (t), 23.7 (t) and 17.8 (q); [Found: $(M - H)^+$, 251.1270. $C_{14}H_{19}O_4$ requires *M*, 251.1283].

Compound **12b** was obtained from **11b** in 93% yield as a white wax; $[\alpha]_D^{29}$ −22.4 (*c* 1.63, $CHCl_3$); δ_H (400 MHz, $CDCl_3$): 6.97 (1H, dd, *J* 4.9 and 15.6), 6.15 (1H, dd, *J* 1.0 and 15.6), 5.85 (1H, qd, *J* 6.6 and 15.4), 5.48 (1H, qdd, *J* 1.7, 8.0 and 15.4), 4.25 (1H, ddd, *J* 1.7, 4.9 and 8.4), 4.10 (1H, t, *J* 8.4), 1.75 (3H, dd, *J* 1.7 and 6.6), 1.63–1.70 (8H, m) and 1.41–1.44 (2H, m); δ_C (100 MHz, $CDCl_3$): 171.3 (s), 146.3 (d), 132.7 (d), 126.6 (d), 121.4 (d), 110.4 (s), 81.5 (d), 79.3 (d), 36.6 (t), 36.2 (t), 25.0 (t), 23.8 (t), 23.7 (t) and 17.8 (q); [Found: M^+, 252.1349. $C_{14}H_{20}O_4$ requires *M*, 252.1362].

(4*R*,5*S*,6*E*)- and (4*S*,5*S*,6*E*)-4,5-*O*-Cyclohexylidene-6-octenoic acid 13a and 13b

To a solution of **12a** (19.2 mg, 0.076 mmol) in ethanol (2 cm^3) was added sodium borohydride (10.4 mg, 0.25 mmol), and the mixture was stirred at 40 °C for 15 h. A small amount of 1 M hydrochloric acid was, with cooling, added to decompose excess sodium borohydride, and the mixture was extracted with ether. The extract was washed with water, dried and concentrated. The residue was purified by chromatography to give **13a** (16.9 mg, 87%) as a colorless oil; $[\alpha]_D^{29}$ +20.1 (*c* 0.73, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 5.79 (1H, qd, *J* 6.4 and 15.2), 5.46 (1H, qdd, *J* 1.5, 8.4 and 15.2), 4.51 (1H, dd, *J* 6.1 and 8.4), 4.09 (1H, ddd, *J* 4.7, 6.1 and 9.3), 2.39–2.61 (2H, m), 1.68–1.79 (2H, m), 1.73 (3H, dd, *J* 1.5 and 6.4), 1.58–1.65 (8H, m) and 1.38–1.40 (2H, m); δ_C (100 MHz, $CDCl_3$): 179.1 (s), 131.0 (d), 126.6 (d), 108.8 (s), 79.0 (d), 76.8 (d), 38.1 (t), 35.1 (t), 30.7 (t), 26.1 (t), 25.1 (t), 24.1 (t), 23.8 (t) and 17.9 (q); [Found: M^+, 254.1512. $C_{14}H_{22}O_4$ requires *M*, 254.1518].

Compound **13b** was obtained from **12b** in 98% yield as a colorless oil; $[\alpha]_D^{31}$ −19.4 (*c* 1.34, $CHCl_3$); ν_{max}(film)/cm^{-1} 2935, 2862, 2669, 1711, 1448, 1364 and 1113; δ_H (400 MHz, $CDCl_3$): 5.82 (1H, qd, *J* 6.6 and 15.4), 5.42 (1H, qdd, *J* 1.5, 8.0 and 15.4), 3.98 (1H, dd, *J* 8.0 and 8.3), 3.66 (1H, dt, *J* 3.6 and 8.3), 2.44–2.62 (2H, m), 1.89–1.98 (1H, m), 1.77–1.84 (1H, m), 1.73 (3H, dd, *J* 1.5 and 6.6), 1.59–1.61 (8H, m) and 1.36–1.40 (2H, m); δ_C (100 MHz, $CDCl_3$): 179.1 (s), 131.1 (d), 126.6 (d), 109.1 (s), 81.9 (d), 78.9 (d), 36.7 (t), 36.5 (t), 30.6 (t), 26.1 (t), 25.1 (t), 24.1 (t), 23.8 (t) and 17.9 (q); [Found: M^+, 254.1514. $C_{14}H_{22}O_4$ requires *M*, 254.1518].

(4*R*)-4-[(1′*S*,2′*E*)-1′-Hydroxy-2′-butenyl]-4-butanolide 1a (musacin E) and (4*S*)-4-[(1′*S*,2′*E*)-1′-hydroxy-2′-butenyl]-4-butanolide 1b

To a solution of **13a** (15.5 mg, 0.06 mmol) in 1,4-dioxane (3 cm^3) was added concentrated hydrochloric acid (0.5 cm^3), and the mixture was stirred at 50 °C for 12 h. The reaction mixture was diluted with water, and extracted with ether. The extract was washed with water, dried and concentrated. The resultant oil was purified by chromatography (hexane–ethyl acetate, 2 : 1) to give **1a** (7.5 mg, 79%) as a colorless oil; $[\alpha]_D^{21}$ +10.9 (*c* 0.10, $CHCl_3$); {ref. 1 $[\alpha]_D^{20}$ +10.8 (*c* 0.3, $CHCl_3$)}; δ_H (300 MHz, $CDCl_3$): 5.87 (1H, dqd, *J* 1.0, 6.6 and 15.4 Hz), 5.44 (1H, qdd, *J* 1.7, 6.6 and 15.4), 4.50 (1H, dt, *J* 3.1 and 7.3), 4.37–4.44 (1H, m), 2.49–2.61 (2H, m), 2.15–2.25 (2H, m), 1.94 (1H, d, *J* 3.6, OH) and 1.74 (3H, ddd, *J* 1.0, 1.5 and 6.6); δ_C (100 MHz, $CDCl_3$): 177.4 (s), 130.4 (d), 127.4 (d), 82.3 (d), 72.8 (d), 28.5 (t), 21.3 (t) and 17.9 (q); [Found: $(M + H)^+$, 157.0837. $C_8H_{13}O_3$ requires *M*, 157.0865].

Compound **1b** was obtained from **13b** in 68% yield as a colorless oil; $[\alpha]_D^{28}$ +35.2 (*c* 0.20, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 5.86 (1H, dqd, *J* 1.0, 6.6 and 15.4), 5.52 (1H, qdd, *J* 1.7, 6.3 and 15.4), 4.44 (1H, dt, *J* 5.4 and 7.1), 4.09 (1H, br t, *J* 6.4), 2.50–2.61 (2H, m), 2.05–2.26 (2H, m) and 1.74 (3H, dd, *J* 1.0 and 6.3); δ_C (75 MHz, $CDCl_3$): 177.1 (s), 130.8 (d), 127.9 (d), 82.7 (d), 74.9 (d), 28.4 (t), 23.7 (t) and 17.8 (t); [Found: $(M + H)^+$, 157.0837. $C_8H_{13}O_3$ requires *M*, 157.0865].

(4*S*)-4-[(1′*R*,2′*E*)-1′-Hydroxy-2′-butenyl]-4-butanolide 1c

To a mixture of **1b** (16 mg, 0.10 mmol), triphenylphosphine (54 mg, 0.21 mmol), benzoic acid (25 mg, 0.21 mmol) in THF (7 cm^3) was added diethyl azodicarboxylate (0.02 cm^3, 0.21 mmol) in THF (2 cm^3), and the mixture was stirred for 23 h at room temperature. After concentration the resultant oil was purified by chromatography (hexane–ethyl acetate, 3 : 1) to give the benzoate (24.5 mg, 94%) as a colorless oil; $[\alpha]_D^{30}$ +24.6 (*c* 1.40, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 8.01–8.04 (2H, m), 7.41–7.60 (3H, m), 5.99 (1H, dq, *J* 6.6 and 15.0), 5.63 (1H, dd, *J* 3.3 and 7.6), 5.54 (1H, ddq, *J* 1.5, 7.6 and 15.0 Hz), 4.74 (1H, ddd,

J 0.9, 3.5 and 6.8), 2.48–2.68 (2H, m), 2.16–2.42 (2H, m) and 1.76 (3H, dd, *J* 1.5 and 6.6); δ_C (100 MHz, $CDCl_3$): 176.7 (s), 165.4 (s), 133.6 (s), 133.2 (d), 129.6 (d), 128.4 (d), 128.1 (d), 123.3 (d), 80.3 (d), 75.5 (d), 27.9 (t), 22.8 (t) and 18.0 (q); [Found: M^+, 260.1031. $C_{15}H_{16}O_4$ requires *M*, 260.1049].

Hydrolysis of the benzoate with KOH in ethanol–water gave **1c** (12.6 mg, 79%) as a colorless oil; $[\alpha]_D^{27}$ −13.0 (*c* 0.28, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 5.87 (1H, dqd, *J* 1.1, 6.6 and 15.4), 5.44 (1H, qdd, *J* 1.7, 6.6 and 15.4), 4.48–4.51 (1H, m), 4.37–4.41 (1H, m), 2.53–2.56 (2H, m), 2.18–2.22 (2H, m) and 1.74 (3H, ddd, *J* 0.9, 1.5 and 6.6); δ_C (75 MHz, $CDCl_3$): 177.4 (s), 130.4 (d), 127.4 (d), 82.3 (d), 72.8 (d), 28.5 (t), 21.3 (t) and 17.9 (q); [Found: $(M + H)^+$, 157.0837. $C_8H_{13}O_3$ requires *M*, 157.0865].

General procedure for coupling of 12 with 14

To a mixture of **14**[8] (38.3 mg, 0.18 mmol) and the carboxylic acid **12** (50.3 mg, 0.20 mmol) in dichloromethane (20 cm^3) were added 4-dimethylaminopyridine (68.7 mg, 0.56 mmol), camphorsulfonic acid (10 mg), and 1,3-dicyclohexylcarbodiimide (116.0 mg, 0.56 mmol) at 0 °C. After stirring for 19 h at room temperature, the mixture was concentrated. The residue (an isomeric mixture) was separated by chromatography (hexane–ethyl acetate, 4 : 1) to give **15** or **17**.

(2*S*,3*R*)- and (2*S*,3*S*)-3-[(4′*R*,5′*S*,2′*E*,6′*E*)-4′,5′-*O*-Cyclohexylidene-1′-oxooct-2′,6′-dienyoxylmethyl]-2-tetrahydropyranyloxy-4-butanolide 15a and 15b

These compounds were obtained from **12a** and **14a**.

15a: 47% yield (colorless oil); $[\alpha]_D^{22}$ −64.5 (*c* 0.75, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 6.85 (1H, dd, *J* 4.9 and 15.5), 6.09 (1H, dd, *J* 1.1 and 15.5), 5.83 (1H, qd, *J* 6.5 and 15.2 Hz), 5.32 (1H, qdd, *J* 1.5, 8.2 and 15.2), 5.16–5.18 (1H, m), 4.73 (1H, dd, *J* 1.1 and 7.0), 4.67 (1H, dd, *J* 7.0 and 8.3), 4.48 (1H, d, *J* 8.8), 4.43 (1H, dd, *J* 4.1 and 11.7), 4.32 (1H, dd, *J* 6.4 and 11.7), 4.28 (1H, d, *J* 9.3), 4.07 (1H, dd, *J* 9.3 and 9.4), 3.51–3.58 (1H, m), 3.17 (1H, m), 2.87–2.99 (1H, m), 1.72 (3H, dd, *J* 1.5 and 6.5), 1.57–1.83 (14H, m) and 1.40–1.45 (2H, m); δ_C (75 MHz, $CDCl_3$): 174.6 (s), 165.6 (s), 146.1 (d), 132.0 (d), 126.2 (d), 121.1 (d), 110.0 (s), 97.9 (d), 79.2 (d), 76.9 (d), 70.7 (d), 67.1 (t), 62.6 (t), 61.9 (t), 41.7 (d), 37.6 (t), 34.7 (t), 30.1 (t), 25.2 (t), 25.0 (t), 24.0 (t), 23.7 (t), 19.0 (t) and 17.8 (q); [Found: M^+, 450.2248. $C_{24}H_{34}O_8$ requires *M*, 450.2254].

15b: 22% yield (colorless oil); $[\alpha]_D^{23}$ −6.7 (*c* 0.5, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 6.83 (1H, dd, *J* 5.0 and 15.6), 6.09 (1H, dd, *J* 0.9 and 15.6), 5.83 (1H, qd, *J* 6.6 and 15.0), 5.33 (1H, dd, *J* 7.5 and 15.0), 5.11 (1H, m), 4.66–4.73 (2H, m), 4.62 (1H, d, *J* 7.9), 4.48 (1H, dd, *J* 4.6 and 11.6), 4.27–4.39 (3H, m), 3.78–3.85 (1H, m), 3.53–3.60 (1H, m), 2.94–3.04 (1H, m), 1.73 (3H, d, *J* 6.6), 1.57–1.80 (14H, m) and 1.41–1.42 (2H, m); δ_C (75 MHz, $CDCl_3$): 174.7 (s), 166.1 (s), 146.1 (d), 132.4 (d), 126.6 (d), 121.9 (d), 110.3 (s), 98.4 (d), 79.7 (d), 77.4 (d), 69.7 (d), 68.0 (t), 63.1 (t), 61.5 (t), 39.2 (d), 38.0 (t), 35.2 (t), 30.4 (t), 25.6 (t), 25.5 (t), 24.4 (t), 24.1 (t), 19.4 (t) and 18.2 (q); [Found: M^+, 450.2235. $C_{24}H_{34}O_8$ requires *M*, 450.2254].

(2*S*,3*R*)- and (2*S*,3*S*)-3-[(4′*S*,5′*S*,2′*E*,6′*E*)-4′,5′-*O*–Cyclohexylidene-1′-oxooct-2′,6′-dienyloxymethyl]-2-tetrahydropyranyloxy-4-butanolide 15c and 15d

These compounds were obtained from **12b** and **14a**.

15c: 43% yield (colorless oil); δ_H (400 MHz, $CDCl_3$): 6.90 (1H, dd, *J* 4.6 and 15.6), 6.15 (1H, dd, *J* 1.7 and 15.6), 5.85 (1H, qd, *J* 6.6 and 15.4), 5.47 (1H, qdd, *J* 1.7, 8.0 and 15.4), 5.15–5.18 (1H, m), 4.47 (1H, dd, *J* 8.3 and 9.0), 4.424 (1H, d, *J* 9.5), 4.416 (1H, dd, *J* 4.0 and 11.5), 4.33 (1H, dd, *J* 6.6 and 11.5), 4.23 (1H, ddd, *J* 1.7, 4.9 and 8.6), 4.05–4.13 (2H, m), 3.78–3.84 (1H, m), 3.52–3.56 (1H, m), 2.88–2.98 (1H, m), 1.75 (3H, dd, *J* 1.7 and 6.6), 1.60–1.69 (14H, m) and 1.41–1.43 (2H, m); δ_C (100 MHz, $CDCl_3$): 174.5 (s), 165.6 (s), 140.5 (d), 132.6 (d), 126.6 (d), 121.0 (d), 110.3 (s), 97.9 (d), 81.5 (d), 79.3 (d), 70.8 (d), 67.0 (t), 62.5 (t), 62.0 (t), 41.7 (d), 36.6 (t), 36.2 (t), 30.0 (t), 25.1 (t), 25.0 (t), 23.75 (t), 23.69 (t), 19.0 (t) and 17.8 (q); [Found: M^+, 450.2248. $C_{24}H_{34}O_8$ requires *M*, 450.2254].

15d: 28% yield (colorless oil); δ_H (400 MHz, $CDCl_3$): 6.86 (1H, dd, *J* 5.1 and 15.6), 6.11 (1H, dd, *J* 1.5, and 15.6), 5.85 (1H, qd, *J* 6.6 and 15.4), 5.47 (1H, qdd, *J* 1.5, 8.0 and 15.4), 5.09 (1H, d, *J* 6.8), 4.62 (1H, d, *J* 7.8), 4.47 (1H, dd, *J* 4.6 and 11.4), 4.30–4.39 (3H, m), 4.19–4.23 (1H, m), 4.09 (1H, dd, *J* 7.6 and 8.6), 3.79–3.84 (1H, m), 3.55–3.57 (1H, m), 2.95–3.02 (1H, m), 1.75 (3H, dd, *J* 1.5 and 6.6), 1.62–1.69 (14H, m) and 1.40–1.41 (2H, m); δ_C (100 MHz, $CDCl_3$): 174.2 (s), 165.6 (s), 144.6 (d), 132.4 (d), 126.6 (d), 121.4 (d), 110.2 (s), 98.0 (d), 81.5 (d), 79.4 (d), 69.3 (d), 67.6 (t), 62.7 (t), 61.1 (t), 38.8 (d), 36.6 (t), 36.1 (t), 29.9 (t), 25.1 (t), 24.9 (t), 23.7 (t), 23.6 (t), 19.0 (t) and 17.8 (q); [Found: M^+, 450.2248. $C_{24}H_{34}O_8$ requires *M*, 450.2254].

General procedure for acid hydrolysis of THP and cyclohexylidene groups

A solution of **15** or **17** (17.8 mg, 0.04 mmol) in acetic acid (2 cm^3), THF (1 cm^3), and water (0.5 cm^3) was stirred at 80 °C. After stirring for 4 h the mixture was concentrated. The residue was purified by chromatography on silica gel (10 g) with ethyl acetate to give **2** or **3**.

(2*S*,3*R*)-4′,5′-Dihydroxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-hydroxy-4-butanolide 2a (musacin B_1) and (2*S*,3*S*)-3-[(4′*R*,5′*S*,2′*E*,6′*E*)-4′,5′-dihydroxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-hydroxy-4-butanolide 2b

Compound **2a** was obtained from **15a** in 72% yield as a colorless oil; $[\alpha]_D^{26}$ −17.0 (*c* 0.36, MeOH); {ref. 1 $[\alpha]_D^{17}$ −10.1 (*c* 0.4, MeOH)}; δ_H (500 MHz, CD_3OD): 7.08 (1H, dd, *J* 4.5 and 15.5), 6.09 (1H, dd, *J* 1.5 and 15.5), 5.74 (1H, dqd, *J* 1.0, 6.5 and 15.5), 5.53 (1H, qdd, *J* 1.5, 7.5 and 15.5), 4.44 (1H, dd, *J* 8.0 and 9.0), 4.41 (1H, dd, *J* 4.0 and 11.5), 4.32 (1H, d, *J* 10.0), 4.30 (1H, dd, *J* 6.5 and 11.5), 4.14 (1H, ddd, *J* 1.5, 4.5 and 5.5), 4.06 (1H, dd, *J* 9.5 and 10.0), 3.98 (1H, dd, *J* 5.5 and 7.5), 2.76–2.79 (1H, m) and 1.71 (3H, dd, *J* 1.5 and 6.5); δ_C (75 MHz, CD_3OD): 178.5 (s), 167.6 (s), 150.3 (d), 131.4 (d), 129.6 (d), 121.6 (d), 76.4 (d), 75.1 (d), 69.9 (d), 68.1 (t), 63.3 (t), 44.9 (d) and 18.0 (q); [Found: $(M - H)^+$, 285.0970. $C_{13}H_{17}O_7$ requires *M*, 285.0974].

Compound **2b** was obtained from **15b** in 60% yield as a colorless oil; $[\alpha]_D^{21}$ +51.8 (*c* 0.34, MeOH); δ_H (500 MHz, CD_3OD): 7.02 (1H, dd, *J* 5.0 and 15.5), 6.03 (1H, dd, *J* 2.0 and 15.5), 5.74 (1H, qd, *J* 6.5 and 15.5), 5.54 (1H, qdd, *J* 1.5, 7.0 and 15.5), 4.63 (1H, d, *J* 8.0), 4.40 (1H, dd, *J* 6.0 and 9.5), 4.37 (1H, dd, *J* 4.0 and 11.5), 4.29 (1H, dd, *J* 2.0 and 9.5), 4.24 (1H, dd, *J* 5.5 and 11.5), 4.14 (1H, ddd, *J* 2.0, 5.0 and 6.5), 3.98 (1H, dd, *J* 6.5 and 7.0), 2.90–2.93 (1H, m) and 1.71 (3H, dd, *J* 1.5 and 6.5); δ_C (75 MHz, CD_3OD): 178.8 (s), 167.7 (s), 150.1 (d), 131.3 (d), 129.6 (d), 121.7 (d), 76.4 (d), 75.2 (d), 69.1 (d), 68.3 (t), 62.5 (t), 40.5 (d) and 18.0 (q); [Found: $(M - H)^+$, 285.0965. $C_{13}H_{17}O_7$ requires *M*, 285.0974].

(2*S*,3*R*)- and (2*S*,3*S*)-3-[(4′*S*,5′*S*,2′*E*,6′*E*)-4′,5′-Dihydroxy-1′-oxooct-2′,6′-dienyloxy-methyl]-2-hydroxy-4-butanolide 2c and 2d

Compound **2c** was obtained from **15c** in 72% yield as a colorless oil; $[\alpha]_D^{28}$ −70.0 (*c* 0.39, MeOH); δ_H (400 MHz, CD_3OD): 7.02 (1H, dd, *J* 4.4 and 15.6), 6.09 (1H, dd, *J* 1.7 and 15.6), 5.74 (1H, qd, *J* 6.4 and 15.4), 5.48 (1H, qdd, *J* 1.5, 7.3 and 15.4), 4.44 (1H, dd, *J* 8.3 and 8.8), 4.40 (1H, dd, *J* 4.4 and 11.5), 4.31 (1H, d, *J* 11.2), 4.30 (1H, dd, *J* 6.1 and 11.2), 4.17 (1H, ddd, *J* 1.7, 4.4 and 5.9), 4.06 (1H, dd, *J* 9.3 and 10.0), 3.96 (1H, dd, *J* 5.9 and 7.4), 2.76–2.79 (1H, m) and 1.70 (3H, dd, *J* 1.5 and 6.4); δ_C (100 MHz, CD_3OD): 178.5 (s), 167.6 (s), 150.2 (d), 131.1 (d), 130.1 (d), 121.5 (d), 76.4 (d), 75.1 (d), 69.9 (d), 68.1 (t), 63.3 (t), 44.9 (d) and 18.0 (q); [Found: $(M - H)^+$, 285.0965. $C_{13}H_{17}O_7$ requires *M*, 285.0974].

Compound **2d** was obtained from **15d** in 61% yield as a colorless oil; $[\alpha]_D^{28}$ +5.6 (*c* 0.28, MeOH); δ_H (400 MHz, CD_3OD): 6.97 (1H, dd, *J* 4.4 and 15.6), 6.04 (1H, dd, *J* 1.7 and 15.6), 5.74 (1H, qd, *J* 6.6 and 15.4), 5.49 (1H, qdd, *J* 1.5, 7.3 and 15.4), 4.62 (1H, d, *J* 8.1), 4.40 (1H, dd, *J* 6.4 and 9.8), 4.36 (1H, dd, *J* 3.9 and 11.2), 4.29 (1H, dd, *J* 2.2 and 9.8), 4.25 (1H, dd, *J* 5.6 and 11.2), 4.13 (1H, ddd, *J* 1.7, 4.4 and 6.1), 3.94 (1H, dd, *J* 6.1 and 7.4), 2.90–2.94 (1H, m) and 1.71 (3H, dd, *J* 1.5 and 6.6); δ_C (100 MHz, CD_3OD): 178.8 (s), 167.7 (s), 150.0 (d), 131.1 (d), 130.1 (d), 121.7 (d), 76.4 (d), 75.2 (d), 69.1 (d), 68.3 (t), 62.5 (t), 40.5 (d) and 18.0 (q); [Found: $(M - H)^+$, 285.0969. $C_{13}H_{17}O_7$ requires *M*, 285.0974].

General procedure for acetylation of triols 2 and 3

To a solution of **2** or **3** (10.9 mg, 0.038 mmol) in acetic anhydride (1 cm^3) and pyridine (1.5 cm^3) was stirred at room temperature. After stirring for 6 h the mixture was concentrated. The residue was purified by chromatography on silica gel (10 g) with hexane–ethyl acetate (1 : 1) to give **16** or **18**.

(2*S*,3*R*)- and (2*S*,3*S*)-3-[(4′*R*,5′*S*,2′*E*,6′*E*)-4′,5′-Diacetoxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-acetoxy-4-butanolide 16a and 16b

Compound **16a** was obtained from **2a** in 78% yield as a colorless oil; $[\alpha]_D^{22}$ −34.2 (*c* 0.21, $CHCl_3$); δ_H (300 MHz, CD_3OD): 6.89 (1H, dd, *J* 5.3 and 15.8), 6.01 (1H, dd, *J* 1.7 and 15.8), 5.86 (1H, qd, *J* 6.4 and 15.2), 5.80–5.86 (1H, m), 5.57 (1H, ddd, *J* 1.6, 3.7 and 5.2), 5.44 (1H, d, *J* 9.5), 5.40–5.43 (1H, m), 4.54 (1H, dd, *J* 8.8 and 9.0), 4.38 (1H, dd, *J* 4.4 and 11.7), 4.30 (1H, dd, *J* 5.9 and 11.7), 4.14 (1H, dd, *J* 9.3 and 9.5), 3.00–3.03 (1H, m), 2.19 (3H, s), 2.13 (3H, s), 2.07 (3H, s) and 1.73 (3H, dd, *J* 1.0 and 6.4); δ_C (75 MHz, $CDCl_3$): 171.5 (s), 169.9 (s), 169.7 (s), 169.6 (s), 165.0 (s), 142.5 (d), 133.1 (d), 123.8 (d), 122.5 (d), 74.2 (d), 72.9 (d), 68.8 (d), 66.8 (t), 61.8 (t), 41.0 (d), 21.0 (q), 20.8 (q), 20.5 (q) and 17.9 (q); [Found: $(M + H)^+$, 413.1438. $C_{19}H_{25}O_{10}$ requires *M*, 413.1449].

Compound **16b** was obtained from **2b** in 60% yield as a colorless oil; $[\alpha]_D^{23}$ +73.1 (*c* 0.20, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 6.86 (1H, dd, *J* 5.3 and 15.8), 5.98 (1H, dd, *J* 1.6 and 15.8), 5.80–5.90 (2H, m), 5.63 (1H, d, *J* 8.2), 5.56 (1H, ddd, *J* 1.6, 3.7 and 5.3), 5.42 (1H, dd, *J* 3.3 and 6.8), 4.47 (1H, dd, *J* 5.7 and 9.7), 4.40 (1H, dd, *J* 1.7 and 9.7), 4.30 (1H, dd, *J* 4.4 and 11.7), 4.21 (1H, dd, *J* 5.5 and 11.7), 3.12–3.16 (1H, m), 2.20 (3H, s), 2.12 (3H, s), 2.07 (3H, s) and 1.74 (3H, dd, *J* 1.1 and 6.8); δ_C (75 MHz, $CDCl_3$): 171.3 (s), 169.9 (s), 169.7 (s), 169.6 (s), 165.0 (s), 142.4 (d), 133.0 (d), 123.9 (d), 122.5 (d), 74.2 (d), 72.8 (d), 67.6 (d), 67.5 (t), 61.1 (t), 37.2 (d), 21.0 (q), 20.8 (q), 20.4 (q) and 17.8 (q); [Found: $(M + H)^+$, 413.1455. $C_{19}H_{25}O_{10}$ requires *M*, 413.1449].

(2*S*,3*R*)- and (2*S*,3*S*)-3-[(4′*S*,5′*S*,2′*E*,6′*E*)-4′,5′-Diacetoxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-acetoxy-4-butanolide 16c and 16d

Compound **16c** was obtained from **2c** in 83% yield as a colorless oil; δ_H (300 MHz, $CDCl_3$): 6.87 (1H, dd, *J* 5.1 and 15.8), 5.99 (1H, dd, *J* 1.7 and 15.8), 5.85–5.87 (2H, m), 5.52–5.56 (1H, m), 5.42 (1H, d, *J* 9.5), 5.36–5.38 (1H, m), 4.53 (1H, t, *J* 9.2), 4.38 (1H, dd, *J* 4.6 and 11.7), 4.29 (1H, dd, *J* 6.2 and 11.7), 4.13 (1H, t, *J* 9.5), 3.29–3.31 (1H, m), 2.19 (3H, s), 2.14 (3H, s), 2.07 (3H, s) and 1.72 (3H, d, *J* 6.4); [Found: $(M + H)^+$, 413.1451. $C_{19}H_{25}O_{10}$ requires *M*, 413.1449].

Compound **16d** was obtained from **2d** in 79% yield as a colorless oil; $[\alpha]_D^{29}$ +49.7 (*c* 0.45, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 6.83 (1H, dd, *J* 5.0 and 15.8), 5.95 (1H, dd, *J* 1.7 and 15.8), 5.85–5.86 (1H, m), 5.62 (1H, d, *J* 8.3), 5.51–5.54 (1H, m), 5.37–5.40 (1H, m), 4.46 (1H, dd, *J* 6.0 and 9.9), 4.38 (1H, dd, *J* 1.5 and 9.9), 4.30 (1H, dd, *J* 4.2 and 11.7), 4.19 (1H, dd, *J* 5.7 and 11.7), 3.12–3.16 (1H, m), 2.20 (3H, s), 2.13 (3H, s), 2.08 (3H, s) and 1.73 (3H, dd, *J* 0.9 and 6.5); [Found: $(M + H)^+$, 413.1445. $C_{19}H_{25}O_{10}$ requires *M*, 413.1449].

(2*R*,3*R*)- and (2*R*,3*S*)-3-[(4′*R*,5′*S*,2′*E*,6′*E*)-4′,5′-*O*-Cyclohexylidene-1′-oxooct-2′,6′-dienyloxymethyl]-2-tetrahydropyranyl-4-butanolide 17a and 17b

These compounds were obtained from **12a** and **14b**.

17a: 39% yield (colorless oil); $[\alpha]_D^{23}$ +55.5 (*c* 1.40, $CHCl_3$). δ_H (300 MHz, $CDCl_3$): 6.82 (1H, dd, *J* 5.0 and 15.6), 6.07 (1H, dd, *J* 1.5 and 15.6), 5.82 (1H, qd, *J* 6.6 and 15.0), 5.34 (1H, qdd, *J* 1.5, 8.1 and 15.2), 5.10–5.12 (1H, m), 4.72 (1H, ddd, *J* 1.5, 5.0 and 6.8), 4.68 (1H, d, *J* 8.0), 4.63 (1H, d, *J* 7.8), 4.48 (1H, dd, *J* 4.4 and 11.3), 4.37 (1H, dd, *J* 6.0 and 9.4), 4.27–4.33 (2H, m), 3.78–3.85 (2H, m), 3.53–3.60 (1H, m), 2.94–3.04 (1H, m), 1.72 (3H, dd, *J* 1.5 and 6.6), 1.57–1.67 (14H, m) and 1.41–1.42 (2H, m); δ_C (75 MHz, $CDCl_3$): 174.3 (s), 165.6 (s), 145.7 (d), 131.9 (d), 126.2 (d), 121.4 (d), 109.9 (s), 98.1 (d), 79.2 (d), 77.0 (d), 69.3 (d), 67.6 (t), 62.7 (t), 61.1 (t), 38.8 (d), 37.5 (t), 34.7 (t), 30.0 (t), 25.1 (t), 25.0 (t), 24.0 (t), 23.7 (t), 19.0 (t) and 17.8 (q); [Found: M^+, 450.2251. $C_{24}H_{34}O_8$ requires *M*, 450.2254].

17b: 49% yield (colorless oil); $[\alpha]_D^{24}$ +124.4 (*c* 0.80, $CHCl_3$). δ_H (300 MHz, $CDCl_3$): 6.85 (1H, dd, *J* 4.7 and 15.7), 6.09 (1H, dd, *J* 1.4 and 15.7), 5.83 (1H, qd, *J* 6.6 and 15.2), 5.32 (1H, qdd, *J* 1.5, 8.1 and 15.2), 5.16–5.18 (1H, m), 4.74 (1H, ddd, *J* 1.7, 4.5 and 6.6), 4.68 (1H, dd, *J* 7.1 and 8.0), 4.48 (1H, d, *J* 8.4), 4.43 (1H, d, *J* 9.3), 4.42 (1H, dd, *J* 4.3 and 11.8), 4.34 (1H, dd, *J* 6.2 and 11.8), 4.08 (1H, dd, *J* 9.3 and 9.5), 3.52–3.58 (2H, m), 2.87–3.00 (1H, m), 1.72 (3H, dd, *J* 1.5 and 6.6), 1.59–1.68 (14H, m) and 1.41–1.43 (2H, m); δ_C (75 MHz, $CDCl_3$): 174.6 (s), 165.6 (s), 146.1 (d), 132.0 (d), 126.2 (d), 121.0 (d), 110.0 (s), 97.9 (d), 79.2 (d), 76.9 (d), 70.7 (d), 67.0 (t), 62.5 (t), 61.9 (t), 41.7 (d), 37.6 (t), 34.7 (t), 30.6 (t), 25.2 (t), 25.0 (t), 24.0 (t), 23.7 (t), 19.0 (t) and 17.8 (q); [Found: M^+, 450.2245. $C_{24}H_{34}O_8$ requires *M*, 450.2254].

(2*R*,3*R*)-4′,5′-Dihydroxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-hydroxy-4-butanolide 3a (musacin B_2) and (2*R*,3*S*)-3-[(4′*R*,5′*S*,2′*E*,6′*E*)-4′,5′-dihydroxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-hydroxy-4-butanolide 3b

Compound **3a** was obtained from **17a** in 57% yield as a colorless oil; $[\alpha]_D^{24}$ −23.8 (*c* 0.51, MeOH). δ_H (300 MHz, CD_3OD): 7.02 (1H, dd, *J* 4.4 and 15.8), 6.03 (1H, dd, *J* 1.7 and 15.8), 5.74 (1H, qd, *J* 6.4 and 15.2), 5.53 (1H, qdd, *J* 1.1, 6.8 and 15.2), 4.62 (1H, d, *J* 8.1), 4.41 (1H, dd, *J* 6.3 and 9.5), 4.37 (1H, dd, *J* 3.8 and 11.7), 4.29 (1H, dd, *J* 1.8 and 9.5), 4.24 (1H, dd, *J* 5.7 and 11.7), 4.14 (1H, ddd, *J* 1.7, 5.0 and 6.6), 3.99 (1H, dd, *J* 5.5 and 6.8), 2.89–2.97 (1H, m) and 1.71 (3H, d, *J* 6.4); δ_C (75 MHz, CD_3OD): 178.8 (s), 167.7 (s), 150.1 (d), 131.3 (d), 129.6 (d), 121.7 (d), 76.4 (d), 75.2 (d), 69.1 (d), 68.3 (t), 62.5 (t), 40.5 (d) and 18.0 (q); [Found: $(M - H)^+$, 285.0968. $C_{13}H_{17}O_7$ requires *M*, 285.0974].

Compound **3b** was obtained from **17b** in 50% yield as a colorless oil; $[\alpha]_D^{24}$ +66.8 (*c* 0.26, MeOH); δ_H (500 MHz, CD_3OD): 7.08 (1H, dd, *J* 4.5 and 15.5), 6.09 (1H, dd, *J* 2.0 and 15.5), 5.74 (1H, qd, *J* 6.5 and 15.5), 5.53 (1H, qdd, *J* 1.5, 7.5 and 15.5), 4.44 (1H, dd, *J* 8.0 and 9.0), 4.41 (1H, dd, *J* 4.0 and 11.5), 4.32 (1H, d, *J* 9.8), 4.30 (1H, dd, *J* 6.5 and 11.5), 4.14 (1H, ddd, *J* 2.0, 4.5 and 5.5), 4.06 (1H, dd, *J* 9.5 and 9.8), 3.98 (1H, dd, *J* 6.0 and 7.5), 2.75–2.80 (1H, m) and 1.71 (3H, dd, *J* 1.5 and 6.5); δ_C (75 MHz, CD_3OD): 178.5 (s), 167.6 (s), 150.3 (d), 131.5 (d), 129.6 (d), 121.6 (d), 76.4 (d), 75.1 (d), 69.9 (d), 68.2 (t), 63.3 (t), 45.0 (d) and 18.0 (q); [Found: $(M - H)^+$, 285.0965. $C_{13}H_{17}O_7$ requires *M*, 285.0974].

(2*R*,3*R*)- and (2*R*,3*S*)-3-[(4′*R*,5′*S*,2′*E*,6′*E*)-4′,5′-Diacetoxy-1′-oxooct-2′,6′-dienyloxymethyl]-2-acetoxy-4-butanolide 18a and 18b

Compound **18a** was obtained from **3a** in 91% yield as a colorless oil; $[\alpha]_D^{23}$ −43.1 (*c* 0.34, $CHCl_3$); {ref. 1 $[\alpha]_D^{20}$ −45.5 (*c* 0.4, $CHCl_3$)};

δ_H (300 MHz, $CDCl_3$): 6.85 (1H, dd, *J* 5.1 and 15.8), 5.97 (1H, dd, *J* 1.6 and 15.8), 5.85–5.88 (1H, m), 5.63 (1H, d, *J* 8.2), 5.54 (1H, ddd, *J* 1.6, 3.5 and 5.0), 5.41–5.42 (1H, m), 4.47 (1H, dd, *J* 1.6,3.5 and 5.0), 5.41–5.42 (1H, m), 4.47 (1H, dd, *J* 6.1 and 9.9), 4.39 (1H, dd, *J* 1.5 and 9.9), 4.32 (1H, dd, *J* 4.2 and 11.7), 4.19 (1H, dd, *J* 5.7 and 11.7), 3.12–3.18 (1H, m), 2.20 (3H, s), 2.12 (3H, s), 2.08 (3H, s) and 1.73 (3H, dd, *J* 0.9 and 6.4); δ_C (75 MHz, $CDCl_3$): 171.4 (s), 169.9 (s), 169.7 (s), 169.6 (s), 165.0 (s), 142.4 (d), 133.0 (d), 123.9 (d), 122.4 (d), 74.2 (d), 72.8 (d), 67.54 (d), 67.47 (t), 61.1 (t), 37.3 (d), 21.0 (q), 20.8 (q), 20.4 (q) and 17.8 (q); [Found: $(M + H)^+$, 413.1435. $C_{19}H_{25}O_{10}$ requires *M*, 413.1449].

Compound **18b** was obtained from **3b** in 100% yield as a colorless oil; $[\alpha]_D^{24}$ +61.8 (*c* 0.22, $CHCl_3$); δ_H (300 MHz, CD_3OD): 6.89 (1H, dd, *J* 5.3 and 15.8), 6.02 (1H, dd, *J* 1.6 and 15.8), 5.80–5.86 (2H, m), 5.56 (1H, ddd, *J* 1.6, 3.5 and 5.1), 5.44 (1H, d, *J* 9.5), 5.40–5.42 (1H, m), 4.54 (1H, dd, *J* 8.4 and 9.2), 4.39 (1H, dd, *J* 4.6 and 11.9), 4.30 (1H, dd, *J* 6.1 and 11.9), 4.14 (1H, dd, *J* 9.3 and 9.5), 3.00–3.04 (1H, m), 2.19 (3H, s), 2.13 (3H, s), 2.07 (3H, s) and 1.73 (3H, dd, *J* 0.9 and 6.4); δ_C (75 MHz, $CDCl_3$): 171.5 (s), 169.9 (s), 169.7 (s), 169.6 (s), 165.0 (s), 142.5 (d), 133.0 (d), 123.8 (d), 122.5 (d), 74.2 (d), 72.8 (d), 68.8 (d), 66.8 (t), 61.8 (t), 41.0 (d), 21.0 (q), 20.8 (q), 20.5 (q) and 17.9 (q); [Found: $(M + H)^+$, 413.1439. $C_{19}H_{25}O_{10}$ requires *M*, 413.1449].

(4*R*,5*S*,2*E*,6*E*)-4,5-*O*-Cyclohexylidene-2,6-octadien-1-ol 19

The ester **11a** was treated as in the synthesis of the aldehyde **7a** to give **19** in 72% yield as a colorless oil; $[\alpha]_D^{21}$ +18.4 (*c* 1.09, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 5.89 (1H, dt, *J* 5.1 and 15.4), 5.75 (1H, qd, *J* 6.4 and 15.2), 5.66 (1H, dd, *J* 7.5 and 15.4), 5.41 (1H, qdd, *J* 1.5, 7.9 and 15.2), 4.58 (1H, dd, *J* 6.4 and 8.4), 4.55 (1H, dd, *J* 6.4 and 8.0), 4.16 (2H, d, *J* 5.1), 1.72 (3H, dd, *J* 1.5 and 6.4), 1.57–1.68 (8H, m) and 1.38–1.43 (2H, m); δ_C (75 MHz, $CDCl_3$): 133.2 (d), 130.8 (d), 127.4 (d), 126.9 (d), 109.1 (s), 79.3 (d), 78.5 (d), 62.7 (t), 37.8 (t), 34.9 (t), 25.0 (t), 24.0 (t), 23.7 (t) and 17.8 (q); [Found: M^+, 238.1560. $C_{14}H_{22}O_3$ requires *M*, 238.1569].

(4*R*,5*S*,2*E*,6*E*)-4,5-*O*-Cyclohexylidene-2,6-octadienal 20

The diol **19** was treated as in the synthesis of the aldehyde **7b** to give **20** in 84% yield as a colorless oil; $[\alpha]_D^{26}$ +74.5 (*c* 2.17, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 9.60 (1H, d, *J* 8.0), 6.69 (1H, dd, *J* 5.1 and 15.6), 6.34 (1H, ddd, *J* 1.5, 7.9 and 15.6), 5.85 (1H, qd, *J* 6.5 and 15.2), 5.33 (1H, qdd, *J* 1.7, 8.4 and 15.2), 4.83 (1H, ddd, *J* 1.5, 5.1 and 7.3), 4.72 (1H, dd, *J* 7.3 and 8.2), 1.73 (3H, dd, *J* 1.6 and 6.5), 1.56–1.67 (8H, m) and 1.40–1.45 (2H, m); δ_C (75 MHz, $CDCl_3$): 193.0 (d), 153.1 (d), 132.7 (d), 132.0 (d), 126.0 (d), 110.1 (s), 79.2 (d), 77.0 (d), 37.5 (t), 34.7 (t), 25.0 (t), 24.0 (t), 23.9 (t), 23.6 (t) and 17.7 (q); [Found: M^+, 236.1401. $C_{14}H_{20}O_3$ requires *M*, 236.1412].

(2*R*,3*S*,4′*S*,5′*R*,2′*E*,6′*E*)-2-(4′, 5′-*O*-Cyclohexylidene-2′, 6′-octadienoyl)-2-tetrahydropyranyloxy-3-(*tert*-butyldimethylsilyloxymethyl)-4-butanolide 21

To a solution of LDA, prepared from diisopropylamine (0.34 cm^3, 2.43 mmol) in THF (10 cm^3) and *n*-butyllithum (1.6 *M* in hexane, 1.50 cm^3, 2.43 mmol), was added a solution of the lactone **14c**[8] (322 mg, 0.98 mmol) in THF (1 cm^3) at −78 °C, and the mixture was stirred for 45 min. The aldehyde **19** (163 mg, 0.69 mmol) and hexamethylphosphoric triamide (0.25 cm^3) in THF (1 cm^3) was added over 5 min, and stirred at −78 °C for 1.5 h. The reaction mixture was quenched by addition of saturated aqueous NH_4Cl (2 cm^3) at −78 °C, and extracted with ethyl acetate. The extract was washed with water and brine, dried, and concentrated under reduced pressure. The residue was purified by chromatography (hexane–ethyl acetate, 20 : 1) to give an oil. This oil was stirred with Dess–Martin periodinane (586 mg, 1.38 mmol) in dichloromethane (15 cm^3) at 0 °C for 1 h. The reaction mixture was quenched by addition of saturated aqueous $NaHCO_3$ (10 cm^3) and saturated aqueous sodium thiosulfate (10 cm^3). After removal of the precipitate, the filtrate was extracted with dichloromethane. The organic layer was washed with water and brine, dried, and concentrated under reduced pressure. The residue was purified by chromatography (hexane–ethyl acetate, 10 : 1) to give **21** (314.8 mg, 81%) as a colorless oil; $[\alpha]_D^{22}$ +27.6 (*c*, 1.57, $CHCl_3$); δ_H (300 MHz, $CDCl_3$): 6.90 (1H, dd, *J* 3.3 and 15.4), 6.83 (1H, d, *J* 15.4), 5.81 (1H, qd, *J* 6.4 and 15.0), 5.31 (1H, ddd, *J* 1.7, 8.4 and 15.0), 5.18–5.20 (1H, m), 4.90 (1H, dd, *J* 2.6 and 6.8), 4.75 (2H, dd, *J* 3.4 and 6.8), 4.67 (1H, dd, *J* 7.3 and 8.1), 4.39 (1H, dd, *J* 7.7 and 8.1), 4.19 (1H, dd, *J* 3.3 and 9.3), 3.84–3.94 (1H, m), 3.65 (1H, dd, *J* 8.4 and 9.9), 3.45–3.47 (1H, m), 3.18–3.19 (1H, m), 1.71 (3H, dd, *J* 1.7 and 6.4), 1.54–1.68 (8H, m), 1.41–1.43 (2H, m), 0.85 (9H, s) and 0.03 (6H, s); δ_C (75 MHz, $CDCl_3$): 190.5 (s), 171.9 (s), 144.7 (d), 131.9 (d), 126.5 (d), 124.1 (d), 109.7 (s), 97.4 (d), 83.9 (s), 79.2 (d), 77.2 (d), 68.1 (t), 64.2 (t), 58.2 (t), 48.8 (d), 37.6 (t), 34.7 (t), 30.6 (t), 25.7 (q), 25.0 (t), 24.7 (t), 23.9 (t), 23.6 (t), 20.4 (t), 18.1 (s), 17.8 (q), −5.7 (q) and −5.8 (q); [Found: M^+, 564.3106. $C_{30}H_{48}O_8Si$ requires *M*, 564.3118].

Synthesis of 15a and 17a by the rearrangement reaction

To a solution of **21** (40.7 mg, 0.072 mmol) in THF (7 cm^3) was added tetra-*n*-butylammonium fluoride (1.0 *M* in THF, 0.14 cm^3, 0.14 mmol) at 0 °C under nitrogen, and the mixture was stirred for 20 min at 0 °C. The reaction mixture was quenched with acetic acid (0.2 cm^3) and aqueous NH_4Cl, and extracted with ether. The extract was washed with water and brine, dried and concentrated. The residue was purified by chromatography (hexane–ethyl acetate, 2 : 1) to give **15a** (8.4 mg, 26%), **17a** (5.4 mg, 17%), **14a** and **14b** (6.2 mg) and **13a** (7.7 mg).

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