Mn(III)-Mediated Radical Cyclization for Δ^1-3-Octalone Synthesis

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An efficient and practical synthetic method of Δ^1-3-octalone, which is a versatile building block for the syntheses of polycyclic compounds, has been developed. The dianion of ethyl acetoacetate reacts with cyclohexene-1-carboxaldehyde (**3**) to produce the aldol adduct **6**, which then undergoes Mn(III)-mediated radical cyclization followed by acetate elimination to give Δ^1-3-octalone **4**. A detailed mechanistic insight of Mn(III)-mediated cyclization of **6** has been disclosed.

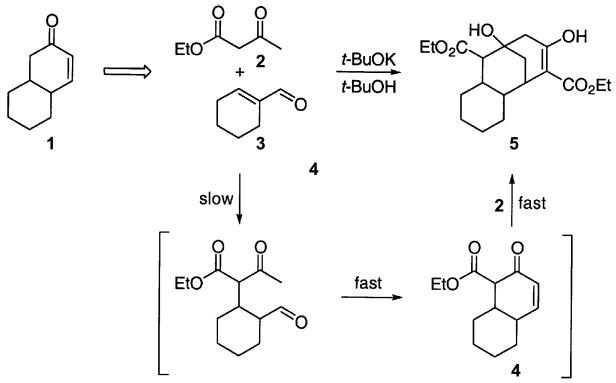
Keywords : Δ^1-3-Octalone, Aldol reaction, $Mn(OAc)_3$, Radical cyclization.

Introduction

Cyclic unsaturated carbonyl compounds are useful building blocks to construct biologically active polycyclic natural products.[1] Diels-Alder reactions of conjugated cyclohexenones with dienes produce octalone derivatives.[2] Octalones, especially Δ^1-3-octalone (**1**) which contains an unsaturated carbonyl group that is ideally disposed for the construction of angularly fused ring structures such as steroid, can be efficiently used as a dienophile in Diels-Alder reaction.[3] Not many literature precedents are, however, available on this attractive strategy to construct angularly fused polycyclic structures mainly due to the inaccessibility to Δ^1-3-octalone (**1**).[4] Herein, we disclose an efficient and practical synthetic method of Δ^1-3-octalone by tandem aldol reaction and Mn(III)-mediated radical cyclization of ethyl acetoacetate (**2**) and cyclohexene-1-carboxaldehyde (**3**). A detailed mechanistic insight of Mn(III)-mediated radical cyclization of the aldol adduct **6** is also described.

Results and Discussion

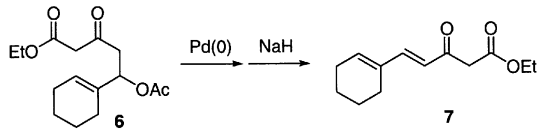
We initially envisaged that tandem Michael addition-aldol condensation of ethyl acetoacetate (**2**) and cyclohexene-1-carboxaldehyde (**3**) would produce Δ^1-3-octalone (**1**) upon decarbethoxylation of the annulation product **4** (Scheme 1).[5] This tandem sequence has been successfully applied to acyclic α,β-unsaturated carbonyl compounds for the efficient synthesis of conjugated cyclohexenones.[6] The success of the above cyclization method lies on the fact that base-catalyzed conjugate addition of the activated methylene unit to acyclic α,β-unsaturated carbonyl compounds proceeds rapidly. Conjugate addition of ethyl acetoacetate (**2**) to cyclic aldehyde **3** is, however, so sluggish comparing to the subsequent intramolecular aldol condensation reaction that the second conjugate addition of ethyl acetoacetate (**2**) and intramolecular aldol reaction sequence proceeds on the initial cyclization product **4** to give rise to the tricyclic compound **5** (Scheme 1).[7]



Scheme 1

In order to circumvent this double cyclization problem producing tricyclic compound **5** instead of bicyclic Δ^1-3-octalone **4**, the order of the tandem cyclization reaction sequence was switched. Dianion of ethyl acetoacetate (**2**) was first reacted with cyclohexene-1-carboxaldehyde (**3**) to give the aldol adduct **6**[8] that was trapped by acetic anhydride to prevent the retro aldol reaction. It was envisioned that intramolecular allylation of β-keto ester **6** would produce the desired octalone skeleton.[9] Base-promoted, Pd(0)-catalyzed intramolecular allylation of **6** was, however, unsuccessful due to the preferable β-elimination of the intermediate π-allylpalladium(II) complex giving rise to the fully conjugated dienyl β-keto ester **7** (Scheme 2).

Mn(III)-mediated radical cyclization of unsaturated β-keto ester **6** was thought to be an ideal strategy to synthesize Δ^1-3-octalone under a non-basic condition.[10] This radical cyclization reaction proceeded smoothly to give 4-carbethoxy-Δ^1-3-octalone (**4**) as a major product after treatment of the initial cyclization product, 4-acetoxy-1-carbethoxy-2-decalone



Scheme 2

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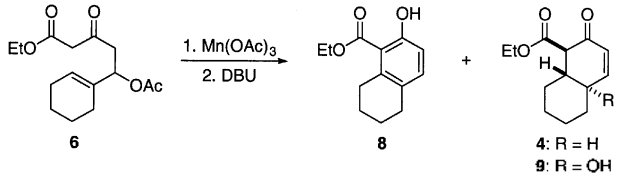
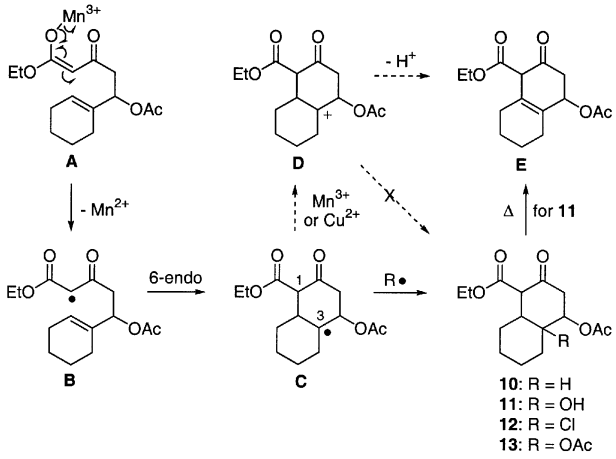


Scheme 3

(**10**) with DBU (Schemes 3 and 4). Further oxidation product, tetrahydronaphthol **8** and Δ^1-3-octalone **9** containing a hydroxyl group at the ring junction were also obtained as minor products. The efforts to optimize the reaction condition as well as to elucidate the mechanistic details (Scheme 4) of the Mn(III)-mediated radical cyclization of β-keto ester **6** are summarized in Table 1.

The desired Δ^1-3-octalone **4** was best obtained using 3 equiv of $Mn(OAc)_3 \cdot 2H_2O$ at 80 °C (entries 4 and 10). Though the reaction was well proceeded even at 25 °C (entry 5), better yields were usually observed at 80 °C. Homolysis of the Mn-O bond in Mn(III) enolate **A** of β-keto ester **6** produces Mn-free, electrophilic radical species **B**,[11] which undergoes 6-endo radical cyclization to give tertiary radical intermediate **C** (Scheme 4).[12] The ratio of the three cyclization products is determined according to the radical termination routes of the tertiary radical intermediate **C**. Hydrogen abstraction from solvent[13] would produce 4-acetoxy-1-carbethoxy-2-decalone (**10**), which gave 4-carbethoxy-Δ^1-3-octalone (**4**) upon DBU treatment. A little better yield of **4** was observed when EtOH was used as solvent, which is known as a better hydrogen donor than AcOH (entries 4 and 10).[14] The possibility of 1,3-hydrogen shift as a hydrogen abstraction mechanism of the tertiary radical **C** was checked because similar 1,5-hydrogen shift was reported in other systems.[14,15] The radical cyclization reaction of **6** was thus studied with 2 equiv of $Mn(OAc)_3 \cdot 2H_2O$ in the presence of 4 equiv of LiCl[14] to give rise to the chloro-substituted decalone **12** only at the tertiary



Scheme 4

radical center in 51% yield, which implied that no 1,3-hydrogen shift was proceeded.

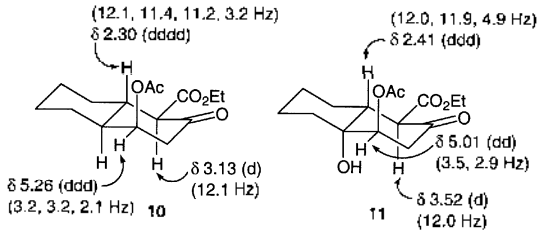
Mn(III) as well as Cu(II) can oxidize the tertiary radical **C** to the tertiary carbocation **D**,[15,16] which would loose proton to give the octalone **E**. This octalone **E** would produce the aromatic tetrahydronaphthol **8** after elimination of the acetate group by DBU and then tautomerization. This oxidation scenario, however, seemed to be a minor process even at 80 °C for the production of tetrahydronaphtol **8**. In fact, no aromatic product **8** was obtained at 25 °C (entries 5, 7, and 9) with or without Cu(II). The amount of **8** was, however, somewhat increased at the expense of **4** and **9** at 80 °C in the presence of Cu(II) (compare entry 3 with 6), which indicated that this oxidation process might work at higher temperature with Cu(II). It was not surprised that no acetoxy-substituted decalone **13** was obtained in any cases, that should be formed through the carbocation intermediate **D**.[15,17]

Abstraction of H_2O[15] by the tertiary radical **C** would produce the hydroxy-substituted decalone **11**, which gave rise to hydroxy-Δ^1-3-octalone **9** after treatment with DBU. The source

Table 1. Mn(III)-mediated radical cyclization reaction of unsaturated β-keto ester **6**

Entry[a]	Equiv of $Mn(OAc)_3$	Solvent	Reaction temp.	Additive (equiv)	Yields of products (%)[b]		
					8	**4**	**9**
1	0.2	AcOH	80 °C	–	7	7	5
2	1	AcOH	80 °C	–	6	25	–
3	2	AcOH	80 °C	–	20	39	6
4	3	AcOH	80 °C	–	18	65	10
5	2	AcOH	25 °C	–	–	44	17
6	2	AcOH	80 °C	$Cu(OAc)_2$ (2)	33	22	–
7	2	AcOH	25 °C	$Cu(OAc)_2$ (2)	–	33	18
8	3	AcOH	80 °C	H_2O (3)	17	30	–
9	3	AcOH	25 °C	H_2O (3)	–	34	22
10	3	EtOH	80 °C	–	12	71	6
11	3	THF[c]	80 °C	4 Å molecular sieve	–	33	–
12	3	THF/H_2O(4 : 1)	80 °C	–	40	4	–

[a]Mn(III)-mediated radical cyclization reactions were performed in 0.1 M solution of the specified solvent at 25 °C for 20 h or at 80 °C for 10 h, and the elimination of acetate was conducted by the reaction with DBU (2 equiv) in THF at 25 °C for 20 h. [b]Isolated yields after silica gel column chromatographic separation. [c]Anhydrous THF was used.



Scheme 5

of moisture could be from the wet solvent and/or hydrated Mn(III) reagent. Practically no differences in the product distributions were observed by the addition of 3 equiv of H_2O to the reaction medium (compare entries 3 with 8, and 5 with 9). On the other hand, hydrated product **9** was not obtained when dry THF was used as solvent with molecular sieves (entry 11). An interesting result was observed when a 4 : 1 mixture of THF and H_2O was used as solvent at 80 °C, where the aromatized product **8** instead of the hydrated product **9** was exclusively obtained (entry 12). This can explain the major route for the formation of tetrahydronaphthol **8** via hydroxydecalone **11**. This idea was supported by the fact that hydroxy-Δ^1-3-octalone **9** in AcOH was quantitatively transformed to tetrahydronaphthol **8** at 80 °C. Furthermore, the amount of the aromatized product **8** was increased at 80 °C by the amount of the hydrated product **9** at 25 °C (compare entries 3 with 5, and 8 with 9).

The stereochemistry of Δ^1-3-octalones **4** and **9** was assigned (Scheme 3) from the coupling constants of the methine hydrogens of the initial radical cyclization products **10** and **11** at 25 °C, respectively (Scheme 5). It was noted that both products have trans ring junctions and that acetoxy groups take axial positions, while carbethoxy groups in equatorial positions.

In summary, a practical synthetic method of Δ^1-3-octalone, an important building block for the synthesis of angularly fused polycyclic compounds, has been developed by tandem aldol reaction and Mn(III)-mediated radical cyclization of ethyl acetoacetate (**2**) and cyclohexene-1-carboxaldehyde (**3**). Detailed mechanism of the radical cyclization reaction of unsaturated β-keto ester **6** has been described. This method constitutes a valuable repertoire for the production of Δ^1-3-octalone, which otherwise required multi-step reaction sequences. This annulation process can be generally applied to any conjugated unsaturated carbonyl compounds through the formation of unsaturated β-keto esters by the aldol reaction with ethyl acetoacetate (**2**).

Experimental Section

General. ^{1}H (300 MHz) and ^{13}C NMR (75.5 MHz) spectra were recorded in deuterated chloroform ($CDCl_3$). Solvents for extraction and chromatography were reagent grade and used as received. The column chromatographies were performed by the method of Still with silica gel 60, 230-400 mesh ASTM supplied by Merck. Solvents used as reaction media were reagent grade and used as received except for THF, which was dried over pre-dried molecular sieve (4 Å) by microwave oven. All reactions were performed under a dry argon atmosphere.

Ethyl 5-acetoxy-5-cyclohexenyl-3-oxopentanoate (6). To a stirred solution of ethyl acetoacetate (4.73 g, 36.3 mmol) in THF (70 mL) was added 60% NaH (2.90 g, 72.6 mmol) at room temperature under Ar atmosphere. The mixture was stirred for 20 min and then cooled to -78 °C. A 1.6 M solution of *n*-BuLi in hexanes (27.2 mL, 43.6 mmol) was added to the mixture. The resulting mixture was stirred for 20 min, and a solution of cyclohexene-1-carboxaldehyde (4.00 g, 36.3 mmol) in THF was added. Stirring for 1 h at -78 °C, the mixture was then treated with acetic anhydride (4.45 g, 43.6 mmol). The reaction mixture was stirred at that temperature for 3 h and quenched with 1 M HCl (40 mL). The mixture was warmed up to room temperature, extracted with ether, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product (14.6 g) was purified by silica gel flash chromatography eluting with a 10% solution of EtOAc in hexanes to give **6** (9.21 g, 32.6 mmol) in 90% yield. Data for **6**: ^{1}H NMR δ 1.28 (3H, t, J = 7.2 Hz), 1.42-1.75 (4H, m), 1.96-2.08 (4H, m), 2.02 (3H, s), 2.81 (1H, d of A part of ABq, J_d = 4.5, J_{AB} = 16.3 Hz), 2.95 (1H, d of B part of ABq J_d = 8.7, J_{AB} = 16.3 Hz), 3.47 (2H, s), 4.20 (2H, q, J = 7.1 Hz), 5.55 (1H, dd, J = 4.5, 8.7 Hz), 5.72 (1H, br s) ppm; ^{13}C NMR δ 14.0, 20.9, 21.9, 22.1, 24.0, 24.6, 45.9, 49.3, 61.2, 72.9, 125.3, 134.6, 166.7, 169.7, 199.4 ppm; IR (neat) 1743, 1649 cm^{-1}; HRMS (EI) calcd for $C_{15}H_{22}O_5$ 282.1467, found 282.1467.

Ethyl 5-cyclohexenyl-3-oxo-4-pentenoate (7). The mixture of $Pd_2(dba)_3$ (152 mg, 0.17 mmol) and PPh_3 (174 mg, 0.67 mmol) in DMF (20 mL) was stirred vigorously at room temperature for 15 min, and a solution of **6** (940 mg, 3.33 mmol) in DMF was added to the mixture. The resulting mixture was stirred for 30 min at that temperature, and 60% NaH (133 mg, 3.33 mmol) was added. The reaction mixture was stirred vigorously at room temperature for 5 h, diluted with ether, washed with 1 M HCl, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product was purified by silica gel flash chromatography eluting with a 10% solution of EtOAc in hexanes to give 7 (399 mg, 1.80 mmol) in 54% yield. Data for 7: ^{1}H NMR δ 1.27 (3H, t, J = 7.2 Hz), 1.60-1.75 (4H, m), 2.16-2.35 (4H, m), 2.34 (2H, s), 4.18 (2H, q, J = 7.2 Hz), 6.03 (1H, br s), 6.56 (1H, d, J = 16.0 Hz), 7.35 (1H, d, J = 16.0 Hz) ppm; ^{13}C NMR δ 14.1, 21.9, 22.1, 24.1, 26.7, 47.3, 61.2, 122.3, 135.1, 141.5, 148.2, 167.6, 192.5 ppm; IR (neat) 1740, 1660, 1588, 1417 cm^{-1}; HRMS (EI) calcd for $C_{13}H_{18}O_3$ 222.1256, found 222.1258.

General procedure for Mn(III)-mediated radical cyclization. To a stirred solution of unsaturated β-keto ester **6** in AcOH under Ar atmosphere was added $Mn(OAc)_3 \cdot 2H_2O$. The mixture was heated to 80 °C for 10 h and cooled to room temperature (or stirred at 25 °C for 20 h). The mixture was treated with 1 M HCl solution and then extracted with EtOAc. The organic phase was washed with saturated $NaHCO_3$ solution, dried over anhydrous Na_2SO_4, filtered, and concent-

rated. The resulting crude cyclization product was dissolved in THF, and treated with DBU. Stirring for 20 h at 25 °C, the mixture was quenched with 1 M HCl solution and then extracted with EtOAc. The organic phase was dried over anhydrous Na_2SO_4, filtered, and concentrated. The crude product was purified by SiO_2 flash column chromatography to give the reported products.

Ethyl 2-hydroxy-5,6,7,8-tetrahydronaphthalene-1-carboxylate (8), ethyl 2-oxo-1,2,4a,5,6,7,8,8a-octahydronaphthalene-1-carboxylate (4) and ethyl 4a-hydroxy-2-oxo-1,2,4a,5,6,7,8,8a-octahydronaphthalene-1-carboxylate (9).

Entry 1, Table 1: The reaction of β-keto ester **6** (752 mg, 2.66 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (0.14 g, 0.53 mmol) in AcOH (27 mL) at 80 °C for 10 h, and then with DBU (0.81 mL, 5.33 mmol) in THF (27 mL) gave **8** (41 mg, 0.19 mmol, 7%), **4** (41 mg, 0.19 mmol, 7%), and **9** (32 mg, 0.13 mmol, 5%).

Entry 2, Table 1: The reaction of β-keto ester **6** (782 mg, 2.77 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (740 mg, 2.77 mmol) in AcOH (28 mL) at 80 °C for 10 h, and then with DBU (0.84 mL, 5.54 mmol) in THF (28 mL) gave **8** (36 mg, 0.16 mmol, 6%) and **4** (154 mg, 0.69 mmol, 25%).

Entry 3, Table 1: The reaction of β-keto ester **6** (758 mg, 2.68 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (1.44 g, 5.37 mmol) in AcOH (27 mL) at 80 °C for 10 h, and then with DBU (0.82 mL, 5.36 mmol) in THF (27 mL) gave **8** (118 mg, 0.54 mmol, 20%), **4** (234 mg, 1.05 mmol, 39%), and **9** (39 mg, 0.16 mmol, 6%).

Entry 5, Table 1: The reaction of β-keto ester **6** (800 mg, 2.83 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (1.52 g, 5.67 mmol) in AcOH (28 mL) at 25 °C for 20 h, and then with DBU (0.86 mL, 5.67 mmol) in THF (36 mL) gave **4** (277 mg, 1.25 mmol, 44%) and **9** (115 mg, 0.48 mmol, 17%).

Entry 6, Table 1: The reaction of β-keto ester **6** (1.08 g, 3.83 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (2.05 g, 7.65 mmol) and $Cu(OAc)_2 \cdot 2H_2O$ (1.53 g, 7.65 mmol) in AcOH (38 mL) at 80 °C for 10 h, and then with DBU (1.16 mL, 7.65 mmol) in THF (38 mL) gave **8** (280 mg, 1.27 mmol, 33%) and **4** (186 mg, 0.84 mmol, 22%).

Entry 7, Table 1: The reaction of β-keto ester **6** (886 mg, 3.14 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (1.68 g, 6.28 mmol) and $Cu(OAc)_2 \cdot 2H_2O$ (1.25 g, 6.28 mmol) in AcOH (30 mL) at 25 °C for 20 h, and then with DBU (0.96 mL, 6.28 mmol) in THF (32 mL) gave **4** (230 mg, 1.04 mmol, 33%) and **9** (135 mg, 0.56 mmol, 18%).

Entry 8, Table 1: The reaction of β-keto ester **6** (948 mg, 3.36 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (2.70 g, 10.1 mmol) in AcOH (34 mL) and H_2O (0.18 mL, 10.1 mmol) at 80 °C for 10 h, and then with DBU (1.02 mL, 6.72 mmol) in THF (34 mL) gave **8** (126 mg, 0.57 mmol, 17%) and **4** (224 mg, 1.01 mmol, 30%).

Entry 9, Table 1: The reaction of β-keto ester **6** (740 mg, 2.62 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (2.11 g, 7.86 mmol) in AcOH (26 mL) and H_2O (0.14 mL, 7.86 mmol) at 25 °C for 20 h, and then with DBU (0.80 mL, 5.24 mmol) in THF (26 mL) gave **4** (198 mg, 0.89 mmol, 34%) and **9** (137 mg, 0.58 mmol, 22%).

Entry 10, Table 1: The reaction of β-keto ester **6** (788 mg, 2.79 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (2.24 g, 8.37 mmol) in EtOH (28 mL) at 80 °C for 10 h, and then with DBU (0.85 mL, 5.58 mmol) in THF (28 mL) gave **8** (74 mg, 0.33 mmol, 12%), **4** (440 mg, 1.98 mmol, 71%), and **9** (40 mg, 0.17 mmol, 6%).

Entry 11, Table 1: The reaction of β-keto ester **6** (780 mg, 2.76 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (2.22 g, 8.28 mmol) in THF (28 mL) in the presence of molecular sieves (4Å, 600 mg) at 80 °C for 10 h, and then with DBU (0.84 mL, 5.52 mmol) in THF (28 mL) gave **4** (203 mg, 0.91 mmol, 33%) exclusively.

Entry 12, Table 1: The reaction of β-keto ester **6** (995 mg, 3.52 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (2.83 g, 10.57 mmol) in THF (28 mL) and H_2O (7 mL) at 80 °C for 10 h, and then with DBU (1.07 mL, 7.04 mmol) in THF (35 mL) gave **8** (310 mg, 1.41 mmol, 40%) and **4** (31 mg, 0.14 mmol, 4%).

Data for **8**: ^{1}H NMR δ 1.42 (3H, t, J = 7.2 Hz), 1.68-1.79 (4H, m), 2.71 (2H, br s), 3.01 (2H, br s), 4.43 (2H, q, J = 7.2 Hz), 6.78 (1H, d, J = 8.6 Hz), 7.13 (1H, d, J = 8.6 Hz), 10.94 (1H, s) ppm; ^{13}C NMR δ 14.2, 22.3, 23.3, 29.6, 29.8, 61.4, 112.4, 115.1, 128.7, 135.8, 139.2, 160.3, 171.7 ppm; IR (neat) 3414, 1738, 1660 cm^{-1}; HRMS (EI) calcd for $C_{13}H_{16}O_3$ 220.1099, found 220.1098. Data for **4**: ^{1}H NMR δ 1.30 (3H, t, J = 7.1 Hz), 1.17-1.45 (4H, m), 1.63-2.00 (4H, m), 2.04-2.20 (2H, m), 3.16 (1H, d, J = 13.2 Hz), 4.25 (2H, q, J = 7.2 Hz), 6.00 (1H, dd, J = 2.5, 10.0 Hz), 6.75 (1H, d, J = 10.0 Hz) ppm; ^{13}C NMR δ 14.2, 25.2, 26.3, 30.6, 31.5, 41.4, 44.0, 61.0, 61.3, 128.2, 155.5, 170.0, 194.9 ppm; IR (neat) 1740, 1681, 1447 cm^{-1}; HRMS (EI) calcd for $C_{13}H_{18}O_3$ 222.1256, found 222.1256. Data for **9**: ^{1}H NMR δ 1.30 (3H, t, J = 7.1 Hz), 1.46-1.82 (8H, m), 2.33 (1H, ddd, J = 3.4, 11.9, 12.5 Hz), 3.59 (1H, d, J = 12.5 Hz), 4.24 (2H, q, J = 7.1 Hz), 5.97 (1H, d, J = 9.9 Hz), 6.73 (1H, d, J = 9.9 Hz) ppm; ^{13}C NMR δ 14.1, 20.8, 24.8, 25.2, 37.4, 44.9, 56.4, 61.1, 66.8, 128.1, 153.1, 170.0, 195.3 ppm; IR (neat) 3480, 1739, 1732, 1682, 1464 cm^{-1}; HRMS (EI) calcd for $C_{13}H_{18}O_4$ 238.1205, found 238.1198.

Ethyl 4-acetoxy-2-oxodecahydronaphthalene-1-carboxylate (10) and ethyl 4-acetoxy-4a-hydroxy-2-oxodecahydronaphthalene-1-carboxylate (11). The reaction of β-keto ester **6** (850 mg, 3.01 mmol) with $Mn(OAc)_3 \cdot 2H_2O$ (1.61 g, 6.02 mmol) in AcOH (30 mL) at 25 °C for 20 h gave **10** (374 mg, 1.32 mmol, 44%) and **11** (152 mg, 0.51 mmol, 17%). Data for **10**: ^{1}H NMR 1.01-1.39 (4H, m), 1.30 (3H, t, J = 7.2 Hz), 1.69-1.83 (5H, m), 2.06 (3H, s), 2.30 (1H, dddd, J = 3.2, 11.2, 11.4, 12.1 Hz), 2.59 (1H, d of A part of ABq, J_d = 3.4, J_{AB} = 14.7 Hz), 2.69 (1H, d of B part of ABq, J_d = 3.1, J_{AB} = 15.0 Hz), 3.13 (1H, d, J = 12.1 Hz), 4.25 (2H, q, J = 7.2 Hz), 5.26 (1H, ddd, J = 2.1, 3.2, 3.2 Hz) ppm; ^{13}C NMR δ 14.2, 21.0, 24.9, 25.7, 28.6, 32.6, 39.2, 43.4, 46.2, 61.0, 63.6, 74.2, 169.1, 170.5, 202.9 ppm; IR (neat) 1741 cm^{-1}; HRMS (CI, H$^+$) calcd for $C_{15}H_{23}O_5$ 283.1546, found 283.1535. Data for **11**: ^{1}H NMR δ 1.28 (3H, t, J = 7.1 Hz), 1.43-1.83 (8H, m), 1.83 (1H, s), 2.08 (3H, s), 2.41 (1H, ddd, J = 4.9, 11.9, 12.0 Hz), 2.50 (1H, d of A part of ABq, J_d = 2.8, J_{AB} = 15.1 Hz), 3.12 (1H, d of B part of ABq, J_d = 3.6, J_{AB} = 15.0 Hz), 3.52

(1H, d, J = 12.0 Hz), 4.25 (2H, q, J = 7.2 Hz), 5.01 (1H, dd, J_d = 2.9, 3.5 Hz) ppm; ^{13}C NMR δ 14.2, 20.7, 21.2, 24.5, 26.5, 34.3, 41.1, 42.5, 59.3, 61.0, 65.9, 70.5, 169.5, 170.0, 203.7 ppm; IR (neat) 3501, 1744, 1716, 1447 cm^{-1}; HRMS (EI) calcd for $C_{15}H_{22}O_6$-[CH_3CO_2H + H_2O] = $C_{13}H_{16}O_3$ 220.1099, found, 220.1097.

Ethyl 4-acetoxy-4a-chloro-2-oxodecahydronaphthalene-1-carboxylate (12). The reaction of β-keto ester **6** (970 mg, 3.43 mmol) with $Mn(OAc)_3{\cdot}2H_2O$ (1.84 g, 6.87 mmol) and LiCl (0.58 g, 13.7 mmol) in AcOH (34 mL) at 25 °C for 20 h gave **12** (555 mg, 1.75 mmol) in 51% yield. Data for **12**: ^{1}H NMR δ 1.29 (3H, t, J = 7.2 Hz), 1.42-1.93 (8H, m), 2.10 (3H, s), 2.14-2.27 (1H, m), 2.59 (1H, d of A part of ABq, J_d = 2.8, J_{AB} = 15.8 Hz), 3.32 (1H, d of B part of ABq, J = 3.9, J_{AB} = 15.8 Hz), 3.48 (1H, d, J = 12.3 Hz), 4.25 (2H, q, J = 7.2 Hz), 5.35 (1H, dd, J_d = 2.9, 3.3 Hz) ppm; ^{13}C NMR δ 14.0, 20.8, 21.0, 24.2, 26.7, 35.5, 42.3, 42.8, 59.8, 61.1, 74.2, 76.7, 168.6, 169.3, 201.8 ppm; IR (neat) 1747, 1720 cm^{-1}; HRMS (EI) calcd for $C_{15}H_{21}ClO_5$ 316.1078, found 316.1075.

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