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Behaviour of monocomplexed 1,4-diynes in the Khand reaction and use of ethylene equivalent techniques in a convenient route to tritium-labelled methyl jasmonate

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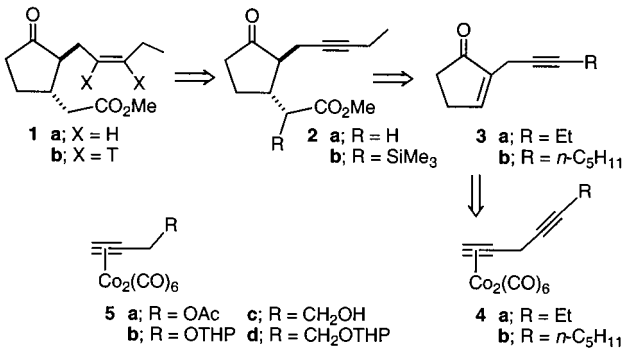
Abstract

1,2-Complexed hexacarbonyl(hepta-1,4-diyne)dicobalt, obtained from hexacarbonyl(propargyl acetate)dicobalt with tri-1-butynylaluminium, has been converted, by selective Khand annulation of the complexed triple bond with vinyl benzoate, to 2-pent-2-yn-1-ylcyclopent-2-en-1-one. By use of standard procedures this alkynyl cyclopentenone has been transformed into methyl jasmonate, allowing replacement of the final hydrogenation step by tritiation to produce the labelled analogue. Two alternative approaches to the intermediate pentynylcyclopentenone were examined and shown to be unsuccessful.

Keywords: Khand reaction; Methyl dehydrojasmonate; Methyl jasmonate; Tritium; Vinyl esters; Ethylene equivalent

1. Introduction

The growing interest in the diverse biological effects of methyl jasmonate, notably as a plant growth regulator and phytoalexin, led to our earlier work demonstrating the effectiveness of the Khand reaction as the key step in the synthesis of both jasmonate itself and a range of analogues [1]. When, therefore, Pharmaceutical Biologists at the Universität München [2] and the Universität Bochum [3] enquired whether we could extend this work to provide a source of tritium-labelled jasmonate, we readily agreed to approach the synthesis of the desired target as described herein.



Scheme 1. Retrosynthetic analysis for the preparation of methyl jasmonates.

2. Results and discussion

2.1. The diyne pathway

We argued that if we approached methyl jasmonate **1a**, viz. its ditritiated form **1b**, via the didehydro compound **2a** we would gain the advantage of (i) placing the labels on sp^2 carbons from which they would be less likely to be lost by exchange, and (ii) adding the radioactive label as late as possible in the synthetic sequence. Moreover, we would have the opportunity of studying a feature of the Khand reaction which had not been previously examined: the behaviour of a diyne complexed specifically on one triple bond. More specifi-

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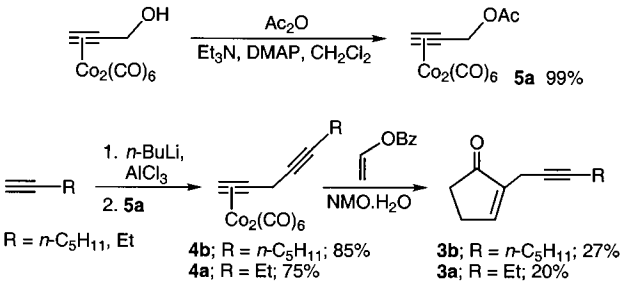
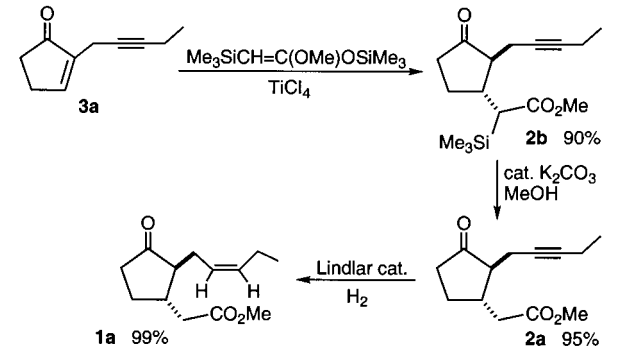


Scheme 2. Preparation of cyclopentenones **3b** and **3a**.

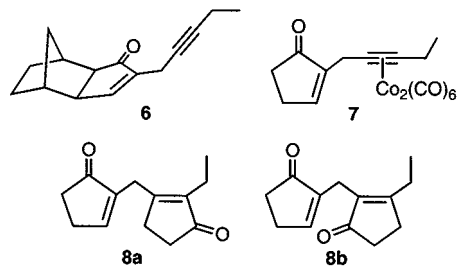


Scheme 3. Completion of methyl jasmonate synthesis.

cally, retrosynthesis from **2a** leads back to the alkyne **3a**, the expected product of a Khand reaction between 1,2-complexed hepta-1,4-diyne **4a** and ethene (Scheme 1). Furthermore, this strategy would thus also allow us to compare another ethene reaction with the use of our novel vinyl ester ethylene equivalent technique as described in the preceding paper [4].

Diyne complexes of the required class had previously been synthesised by Padmanabhan and Nicholas [5] from the propynyl acetate complex **5a** by reaction with a trialkynylaluminium. Since 1-butyne, required in our case, is not widely available, we first tested the reaction sequence using 1-heptyne (Scheme 2). This was treated successively with *n*-butyllithium and aluminium chloride to generate tri-1-heptynylaluminium and then with hexacarbonyl(propargyl acetate)dicobalt **5a** (as an in situ source of the corresponding propargyl cation) to give the mono-complexed diyne **4b** in 85% yield. In due course, *N*-methylmorpholine *N*-oxide monohydrate ($NMO{\cdot}H_2O$) promoted reaction of this complex with vinyl benzoate then produced the desired cyclopentenone **3b**, albeit in a low 27% yield. In turn, this sequence of reactions was then repeated with 1-butyne [6] to give first the diyne complex **4a**, in a good 75% yield, and then the cyclopentenone **3a**, required for the jasmonate synthesis, in 20% yield.

The yield using vinyl benzoate with the monocomplexed diyne **4a** was disappointing, especially based on the efficiency normally achieved with the ethylene equivalent technique [4,7]. Nevertheless, it should be noted that this yield was again better than those obtained when employing ethylene gas and trimethylamine *N*-oxide dihydrate ($TMANO{\cdot}2H_2O$), either under atmospheric (1% yield) or 25 atm. pressure (11% yield). In order to further probe the reactivity of **4a**, we also tested the behaviour of this monocomplexed diyne with a more reactive alkene, norbornene. The formation of the expected tricyclic product **6** in only 30% yield from this alkene undoubtedly reflects the complications introduced by having a diyne system. These were further emphasised when reaction of the complex **4a** with ethylene gas was conducted under 30 atm. pressure with dimethyl sulfoxide as promoter [8]. After a 48 h reaction time at 25 °C, this gave the cyclopentenone **3a** in 10% yield together with its cobalt complex **7** (the product of a metal exchange process) in 12% yield and unreacted complex **4a** (53% recovery). Repetition at 40 °C for 60 h also gave **3a** (12% yield) but now accompanied by the diketone **8a** (or its regioisomer **8b**), resulting from a second Khand reaction, as the major product (23% yield). Therefore, following this series of studies and despite the relatively low yield, it can be seen that the new ethylene equivalent protocol with vinyl benzoate provided the optimum Khand method for the formation of the desired cyclopentenone **3a**.

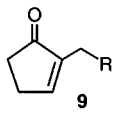


For the final steps of our route towards the methyl jasmonates (Scheme 3), the Michael-type addition of the ketene acetal, $Me_3SiCH{=}C(OMe)OSiMe_3$ [9] to cyclopentenone **3a** followed precedent [1] and gave the silyl-substituted ester **2b** efficiently (90%) [10]. Desilylation of this intermediate to yield methyl dehydrojasmonate **2a** occurred nearly quantitatively on treatment with a catalytic quantity of potassium carbonate in methanol. This method, which had previously been used with silylalkynes [11], seems more convenient and even more efficient than the previously used fluoride treatment [1,9,10]. Finally, hydrogenation of this product **2a** over a Lindlar-type catalyst with either dihydrogen ($^1H_2$) or ditritium ($^3H_2$) [12] gave *cis*-methyl jasmonate **1a**, viz. **1b**, again almost quantitatively.

2.2. Alternative approaches to the jasmonate skeleton

The lower efficiency of the Khand reaction step when using the diyne complex **4a** led us to consider two

alternative approaches to the pent-2-yn-1-ylcyclopentenone (**3a**). The chemistry completed along each of the routes will now be described briefly. In the first of these it was planned to utilise the alcohol **9a** [4a] and, following oxidation to the corresponding aldehyde **9b**, transformation into the alkyne **9c** would require alkylation as a final step on the way to intermediate **3a**. In the second route, the hydroxyl functionality of the lower homologous alcohol **9d** (obtained from Khand cyclisation of **5b** followed by deprotection [4a]) would be converted to a better leaving group with a view to displacement by the anion of 1-butyne.



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9a; R = CH_2OH **9e**; R = CH_2OTHP
9b; R = CHO **9f**; R = OTHP
9c; R = C≡CH **9g**; R = OMs
9d; R = OH **9h**; R = I

The alcohol **9a** was readily formed from but-1-yn-4-ol via its complex **5c** or in better overall yield via the corresponding tetrahydropyranyl ethers **5d** and **9e** [4a]. The tetrahydropyranyl-protected cyclopentenone **9e** was readily deprotected by treatment with catalytic pyridinium para-toluenesulfonate (PPTS) in methanol to afford the alcohol **9a** in 95% yield [4a]. In turn, alcohol **9a** could be oxidised to the rather unstable aldehyde **9b** in 50% yield by treatment with the Dess–Martin periodinane [13]. However, attempts to alkynylate this aldehyde under both Ramirez–Corey [14] and Ohira–Bestmann [15] conditions failed.

As detailed in the preceding paper [4a], the alcohol **9d** was readily formed by PPTS-mediated deprotection of the tetrahydropyranyl derivative **9f** in 99% yield. In order to prepare for the planned nucleophilic displacement by 1-lithiobut-1-yne, the alcohol **9d** was converted into unstable mesylate **9g** (90% yield), which could be further transformed into the equally difficult to handle iodide **9h** (90% yield). Attempts to react either of these intermediates with the aforementioned nucleophile resulted in decomposition. At this stage, work on these two alternative routes to intermediate **3a** was discontinued since neither offered any potential increase in efficiency over our established pathway (vide supra) to the desired methyl jasmonates.

3. Conclusions

We have now shown that complexation of one triple bond of a diyne allows selective Khand reactions to be preformed on that bond. On the other hand, the Khand cyclisation yields which have been obtained are low and, in some cases, the reactions are not clean. Nonetheless, with these monocomplexed diynes our novel vinyl ester ethylene equivalent technique [4] provides the optimum method for the key Khand annulations. This further illustrates the practical advantage of this new procedure and has been shown to provide a short and simple method allowing rapid access to the (labelled) jasmone skeleton.

4. Experimental

4.1. General remarks

See the preceding paper [4a].

4.2. Hexacarbonyl[μ-[(2,3-η:2,3-η)prop-2-yn-1-acetate]]dicobalt-(Co–Co) (5a) [5]

Acetic anhydride (0.18 g, 1.80 mmol) was added to a solution of hexacarbonyl[μ-[(2,3-η:2,3-η)prop-2-yn-1-ol]]dicobalt-(Co–Co) [16] (0.56 g, 1.64 mmol), Et_3N (0.18 g, 1.80 mmol) and *N*,*N*-dimethylaminopyridine (0.01 g, 0.08 mmol) in CH_2Cl_2 (20 ml) at 25 °C. The mixture was stirred for 30 min before it was filtered through a pad of silica using 10% Et_2O in light petroleum as the eluent. The filtrate was evaporated under reduced pressure to give hexacarbonyl[μ-[(2,3-η:2,3-η)prop-2-yn-1-acetate]]dicobalt-(Co–Co) (**5a**) (0.63 g, 99%) as a red oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 2.14$ (3H, s, CH_3CO), 5.28 (2H, s, CH_2), 6.06 (1H, s, ≡CH). ν_{max} (cm^{-1}, CH_2Cl_2): 2096, 2060, 2013, 1724.

4.3. Hexacarbonyl[μ-[(1,2-η:1,2-η)deca-1,4-diyne]]-dicobalt-(Co–Co) (4b)

A solution of *n*-butyllithium in hexanes (2.5 M, 5.20 ml, 13.0 mmol) was added dropwise to a stirred solution of hept-1-yne (1.20 g, 12.5 mmol) in dry hexanes (50 ml) at 0 °C. An immediate precipitation of the lithium acetylide was observed. This white slurry was stirred for 30 min before aluminium trichloride (0.55 g, 4.17 mmol) was added as a finely ground solid. The resulting brown slurry was stirred for a further 1 h before the solvent was evaporated under reduced pressure and replaced with CH_2Cl_2 (60 ml). This mixture was then transferred via cannula to a stirred solution of hexacarbonyl[μ-[(2,3-η:2,3-η)prop-2-yn-1-acetate]]-dicobalt-(Co–Co) (**5a**) (0.50 g, 1.30 mmol) in CH_2Cl_2 (80 ml) at 0 °C. The mixture was stirred for 1 h before sodium sulfate (10.0 g) was added and the slurry was then filtered through a pad of kieselguhr. The filtrate was evaporated under reduced pressure to leave a dark oil, which was purified by repeated (× 3) chromatography through short plugs of silica using light petroleum as the eluent to give *hexacarbonyl*[*μ*-[(*1,2-η:1,2-η*)*deca-1,4-diyne*]]*dicobalt*-(*Co–Co*) (**4b**) (0.46 g, 85%) as a red oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 0.92$ (3H, t, $J = 10.6$ Hz, CH_3), 1.23–1.42 (4H, m, $CH_2CH_2CH_3$), 1.50 (2H, m, ≡CCH_2CH_2), 2.16 (2H, m, ≡CCH_2CH_2) 3.71 (2H, s, ≡CCH_2C≡), 6.06 (1H, s, HC≡). ^{13}C-NMR

(100 MHz, $CDCl_3$): $\delta = 14.1$, 18.8, 22.4, 24.7, 28.4, 31.3, 72.9 (uncomplexed alkyne-C), 82.8 (uncomplexed alkyne-C), 94.6 (complexed alkyne-C), 130.5 (complexed alkyne-C) and 199.8 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 2097, 2053, and 2002.

4.4. 2-(Oct-2-yn-1-yl)cyclopent-2-en-1-one (3b)

A solution of *N*-methylmorpholine *N*-oxide monohydrate (0.93 g, 6.89 mmol) in CH_2Cl_2 (10 ml) was added over a 2 h period (syringe pump) to a stirred solution of hexacarbonyl[μ - [(1,2 - η:1,2 - η)deca - 1,4 - diyne]]dicobalt-(Co–Co) (**4b**) (0.29 g, 0.69 mmol) in vinyl benzoate (15 ml) at 0 °C. The mixture was stirred for 16 h before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using 10% Et_2O in light petroleum as the eluent to give *2-(oct-2-yn-1-yl)cyclopent-2-en-1-one* (**3b**) (35.0 mg, 27%) as a pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 0.92$ (3H, t, $J = 7.1$ Hz, CH_3), 1.21–1.39 (4H, m, CH_2CH_2), 1.53 (2H, m, CH_2), 2.19 (2H, m, ≡CCH_2), 2.46 (2H, m, CH_2CO), 2.61 (2H, m, CH_2CH=), 3.04 (2H, m, =CCH_2C≡), 7.60 (1H, m, CH=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 14.2$, 15.9, 18.9, 22.4, 26.6, 28.9, 31.3, 35.2, 75.9 (alkyne-C), 83.0 (alkyne-C), 143.0 (=C), 159.3 (HC=), 208.4 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 2206, 1702, 1612. HRMS: *m/z*: Found: 190.13652. Calc. for $C_{13}H_{18}O$ [M^+]: 190.13577.

4.5. Hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]-dicobalt-(Co–Co) (4a)

The procedure detailed at Experiment 4.3 was followed with the exception that, at the outset, 1-butyne gas (15.0 g) was slowly bubbled into a stirred solution of *n*-butyllithium (2.5 M (in hexanes), 100 ml, 0.25 mol) in hexanes (250 ml) at −70 °C. The mixture was then allowed to warm to 0 °C after precipitation of the lithium acetylide was observed. Aluminium trichloride (11.1 g, 83.4 mmol), hexacarbonyl[μ-[(2,3-η:2,3-η)prop-2-yn-1-acetate]]dicobalt-(Co–Co) (**5a**) (15.0 g, 39.1 mmol), and CH_2Cl_2 (250 ml and 300 ml) were used to give, after purification, *hexacarbonyl*[*μ*-[(*1,2-η:1,2-η*)*hepta-1,4-diyne*]]*dicobalt*-(*Co–Co*) (**4a**) (11.0 g, 75%) as a red oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 1.14$ (3H, t, $J = 7.5$ Hz, CH_3), 2.18 (2H, q, $J = 7.5$ Hz, CH_2CH_3), 3.71 (2H, s, ≡CCH_2C≡), 6.02 (1H, s, HC≡). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 12.5$, 13.8, 24.7, 72.9 (uncomplexed alkyne-C), 84.0 (uncomplexed alkyne-C), 94.5 (complexed alkyne-C), 125.0 (complexed alkyne-C), 199.3 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 2098, 2047, 2028. HRMS: *m/z*: Found: 349.90357. Calc. for $C_{12}H_8Co_2O_5$ [$M^+ - CO$]: 349.90507.

4.6. Reactions of hexacarbonyl[μ-[(1,2-η:1,2-η)-hepta-1,4-diyne]]dicobalt-(Co–Co) (4a)

4.6.1. Reaction with vinyl benzoate; formation of 2-(pent-2-yn-1-yl)cyclopent-2-en-1-one (3a) [17]

A solution of *N*-methylmorpholine *N*-oxide monohydrate (18.0 g, 0.13 mol) in CH_2Cl_2 (500 ml) was added over a 2 h period (dropping funnel) to a stirred solution of hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]dicobalt-(Co–Co) (**4a**) (5.00 g, 13.2 mmol) in vinyl benzoate (70 ml) at 0 °C. The mixture was stirred for 16 h before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using 10% Et_2O in light petroleum as the eluent to give 2-(pent-2-yn-1-yl)cyclopent-2-en-1-one (**3a**) (0.39 g, 20%) as a pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 1.14$ (3H, t, $J = 7.5$ Hz, CH_3), 2.19 (2H, m, CH_2CH_3), 2.44 (2H, m, CH_2CO), 2.60 (2H, m, CH_2CH=), 3.02 (2H, m, CH_2C≡), 7.60 (1H, m, CH=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 12.6$, 14.4, 15.8, 26.6, 35.1, 75.3 (alkyne-C), 84.2 (alkyne-C), 142.8 (=C), 159.3 (HC=), 208.4 (CO). ν_{max} (cm^{-1}, CH_2Cl_2) 1702, 1638. HRMS: *m/z*: Found: 147.08003. Calc. for $C_{10}H_{11}O$ [$M^+ - 1$]: 147.08099.

4.6.2. Reaction with vinyl acetate; formation of 5-acetoxy-2-(pent-2-yn-1-yl)cyclopent-2-en-1-one

A solution of *N*-methylmorpholine *N*-oxide monohydrate (1.40 g, 10.4 mmol) in CH_2Cl_2 (20 ml) was added over a 4 h period to a stirred solution of hexacarbonyl[μ - [(1,2 - η:1,2 - η)hepta - 1,4 - diyne]]dicobalt-(Co–Co) (**4a**) (0.38 g, 1.00 mmol) in vinyl acetate (20 ml) at −40 °C. The mixture was stirred for a further 16 h before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 10–40% Et_2O in light petroleum gradient as the eluent to give *5-acetoxy-2-(pent-2-yn-1-yl)cyclopent-2-en-1-one* (0.03 g, 13%) as a pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 1.16$ (3H, t, $J = 7.5$ Hz, CH_3CH_2), 2.14 (3H, s, CH_3CO), 2.23 (2H, m, CH_3CH_2), 2.52 (1H, m, CH_2CH=), 3.09 (2H, m, ≡CCH_2C=), 3.14 (1H, m, CH_2CH=), 5.18 (1H, m, CHO), 7.54 (1H, m, HC=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 12.6$, 14.3, 16.1, 20.9, 33.8, 72.6 (CHO), 74.3 (alkyne-C), 84.9 (alkyne-C), 141.3 (CH_2C=), 155.8 (HC=), 170.5 (CO_2), 202.0 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 2190, 1740, 1710. HRMS: *m/z*: Found: 206.09486. Calc. for $C_{12}H_{14}O_3$ [M^+]: 206.09429.

4.6.3. Reaction with ethylene gas at atmospheric pressure

A solution of trimethylamine *N*-oxide dihydrate (1.60 g, 14.4 mmol) in MeOH (9 ml) was added over a 90

min period to a stirred solution of hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]dicobalt-(Co–Co) (**4a**) (0.60 g, 1.59 mmol) in toluene (9 ml), all under 1 atm of ethylene at 25 °C. The mixture was stirred for 16 h before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using 10% Et_2O in light petroleum as the eluent to give 2-(pent-2-yn-1-yl)cyclopent-2-en-1-one (**3a**) (3.0 mg, 1%) as a pale yellow oil. Analytical data were as given above.

4.6.4. Reaction with ethylene gas at 25 atm pressure

A solution of hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]dicobalt-(Co–Co) (**4a**) (0.46 g, 1.20 mmol) in toluene (7 ml) was added to a 50 ml autoclave vessel. A test tube that contained a solution of trimethylamine *N*-oxide dihydrate (1.20 g, 10.8 mmol) in MeOH (7 ml) was then placed inside the autoclave vessel and care was taken to avoid mixing these reactants before the system was placed under 25 atm of ethylene. The mixture was then agitated for 60 h at 25 °C before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using 10% Et_2O in light petroleum as the eluent to give 2-(pent-2-yn-1-yl)cyclopent-2-en-1-one (**3a**) (0.02 g, 11%) as a pale yellow oil. Analytical data were as given above.

*4.6.5. Reaction with norbornene; formation of 3a,4,5,6,7,7a-hexahydro-4,7-methano-2-(pent-2-yn-1-yl)-1H-inden-1-one (**6**)*

A solution of *N*-methylmorpholine *N*-oxide monohydrate (1.20 g, 8.89 mmol) in CH_2Cl_2 (20 ml) was added over a 2 h period (syringe pump) to a stirred solution of hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]dicobalt-(Co–Co) (**4a**) (0.33 g, 0.87 mmol) and norbornene (0.50 g, 5.32 mmol) in CH_2Cl_2 (20 ml) at 25 °C. The mixture was stirred for a further 1 h before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 10–40% Et_2O in light petroleum gradient as the eluent to give *3a,4,5,6,7,7a-hexahydro-4,7-methano-2-(pent-2-yn-1-yl)-1H-inden-1-one* (**6**) (0.06 g, 30%) as a pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 0.86$–1.31 (7H, m), 1.65 (2H, m), 2.20 (4H, m), 2.42 (1H, m), 2.61 (1H, m), 3.07 (2H, s, =CCH$_2$C≡), 7.40 (1H, s, CH=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 13.0$, 14.7, 16.1, 28.9, 29.6, 31.7, 38.6, 39.5, 48.7, 55.0, 75.4 (alkyne-C), 82.7 (alkyne-C), 145.3 (=*C*CH$_2$), 160.9 (HC=), 205.5 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 2206, 1695. HRMS: *m*/*z*: Found: 214.13570. Calc. for $C_{15}H_{18}O$ [M$^+$]: 214.13577.

4.6.6. Reaction with ethylene gas at 30 atm pressure and with Me_2SO as promoter

4.6.6.1. Room temperature reaction. A mixture of dimethyl sulfoxide (1 ml), hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]dicobalt-(Co–Co) (**4a**) (0.79 g, 2.09 mmol) and benzene (30 ml) in a 50 ml autoclave vessel was placed under 30 atm. pressure of ethylene gas and agitated for 48 h at 25 °C. The mixture was then filtered through a pad of silica using Et_2O as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 10–50% Et_2O in light petroleum gradient as the eluent to give *hexacarbonyl[μ-[(2,3-η:2,3-η)-1-[5-oxocyclopent-1-en-1-yl]-pent-2-yne]]dicobalt-(Co–Co)* (**7**) (0.11 g, 12%) as a red oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 1.28$ (3H, t, $J = 7.3$ Hz, CH_3), 2.42 (2H, m, CH_2CO), 2.62 (2H, m, C*H*$_2$CH=), 2.81 (2H, q, $J = 7.3$ Hz, C*H*$_2$CH$_3$), 3.72 (2H, s, =CCH$_2$C≡), 7.51 (1H, t, $J = 2.7$ Hz, HC=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 15.7$, 26.6, 26.9, 28.8, 34.2, 97.0 (alkyne-C), 102.2 (alkyne-C), 144.6 (=*C*CH$_2$), 160.2 (HC=), 200.0 (Co(CO)), 208.7 (C=O). ν_{max} (cm^{-1}, CH_2Cl_2) 2091, 2040, 2008, 1708, 1638. HRMS: *m*/*z*: Found: 377.93811. Calc. for $C_{14}H_{12}Co_2O_5$ [M$^+$ − 2CO]: 377.93633. Also isolated from this reaction were starting complex **4a** (0.42 g, 53%) and the cyclopentenone **3a** (0.03 g, 10%).

4.6.6.2. Reaction at 40 °C. A mixture of dimethyl sulfoxide (1 ml), hexacarbonyl[μ-[(1,2-η:1,2-η)hepta-1,4-diyne]]dicobalt-(Co–Co) (**4a**) (0.32 g, 0.85 mmol) and benzene (30 ml) in a 50 ml autoclave vessel was placed under 30 atm pressure of ethylene gas and agitated for 60 h at 40 °C. The mixture was then filtered through a pad of silica using Et_2O as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 10–50% Et_2O in light petroleum gradient as the eluent to give *2-ethyl-3-[(5-oxocyclopent-1-enyl)methyl]cyclopent-2-en-1-one* (**8a**) *or 3-ethyl-2-[(5-oxocyclopent-1-enyl)methyl]cyclopent-2-en-1-one* (**8b**) (0.04 g, 23%) as a red oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 1.08$ (3H, t, $J = 7.6$ Hz), 2.34 (4H, m), 2.47 (4H, m), 2.48 (2H, m), 3.01 (2H, s), 7.21 (1H, m). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 12.0$, 18.7, 24.5, 26.6, 28.9, 34.3, 34.6, 136.9, 143.4, 159.0, 177.3, 209.2, 209.6. ν_{max} (cm^{-1}, CH_2Cl_2): 1689, 1638. HRMS: *m*/*z*: Found: 204.11591. Calc. for $C_{13}H_{16}O_2$ [M$^+$]: 204.11503. The cyclopentenone **3a** (0.02 g, 12%) was also isolated from this reaction.

*4.7. (3-Oxo-2-(pent-2-yn-1-yl)cyclopentyl)-trimethylsilylacetic acid methyl ester (**2b**) [10]*

Titanium tetrachloride (0.22 g, 2.00 mmol) was added to a stirred solution of 2-(pent-2-yn-1-yl)cyclo-

pent-2-en-1-one (**3a**) (0.27 g, 1.82 mmol) in CH_2Cl_2 (10 ml) at −70 °C. An immediate dark red colour was produced. After 2 min [[1-methoxy-2-(trimethylsilyl)ethenyl]oxy]trimethylsilane (0.44 g, 2.00 mmol) was added dropwise over a 5 min period and the mixture was stirred for a further 1 h before saturated aqueous potassium carbonate (4 ml) was added. The mixture was allowed to warm to room temperature and was then partitioned between CH_2Cl_2 (75 ml) and saturated aqueous potassium carbonate (75 ml). The organic phase was dried and evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 10–20% Et_2O in light petroleum gradient as the eluent to give (3-oxo-2-(pent-2-yn-1-yl)cyclopentyl)trimethylsilylacetic acid methyl ester **2b** (0.48 g, 90%) as a pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 0.17$ (9H, s, $Si(CH_3)_3$), 1.08 (3H, t, $J = 4.8$ Hz, CH_2CH_3), 2.02–2.56 (11H, mm), 3.62 (3H, s, OCH_3). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = -0.9$ ($Si(CH_3)_3$), 12.7, 14.6, 17.5, 24.5, 37.9, 38.2, 40.2, 51.2, 51.8, 76.1 (alkyne-C), 84.2 (alkyne-C), 174.6 (CO_2), 218.2 (CO). ν_{max} (cm^{-1}, CH_2Cl_2) 1746, 1708. HRMS: m/z: Found: 294.16302. Calc. for $C_{16}H_{25}O_3Si$ [$M^+ - 1$]: 294.16512.

4.8. Methyl dehydrojasmonate or (3-oxo-2-(pent-2-yn-1-yl)cyclopentyl)acetic acid methyl ester (2a) [10,18]

Potassium carbonate (0.01 g, 0.07 mmol) was added to a stirred solution of (3-oxo-2-(pent-2-yn-1-yl)cyclopentyl)trimethylsilylacetic acid methyl ester (**2b**) (0.35 g, 1.19 mmol) in MeOH (20 ml) at 25 °C. The mixture was stirred for 4 h before it was diluted with Et_2O and filtered through a pad of silica using Et_2O as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by silica chromatography using a 10–30% Et_2O in light petroleum gradient as the eluent to give methyl dehydrojasmonate or (3-oxo-2-(pent-2-yn-1-yl)cyclopentyl)-acetic acid methyl ester (**2a**) (0.25 g, 95%) as a clear oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 1.04$ (3H, t, $J = 4.8$ Hz, CH_3CH_2), 1.49 (1H, m), 1.89 (1H, m), 2.09 (3H, m), 2.22–2.53 (6H, m), 2.79 (1H, dd, $J = 15.4$, 4.4 Hz), 3.67 (3H, s, OCH_3). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 12.7$, 14.5, 17.9, 27.6, 38.1 ($CH_2C{\equiv}$), 38.3, 39.0 ($CH_2C{\equiv}$), 52.0 ($OCCHCH_2$), 53.3 (OCH_3), 76.2 (alkyne-C), 84.1 (alkyne-C), 172.9 (CO_2), 217.8 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 1740, 1631. HRMS: m/z: Found: 222.12554. Calc. for $C_{13}H_{18}O_3$ [M^+]: 222.12559.

4.9. cis-Methyl jasmonate (1a) [1a,10,17]

Lindlar catalyst (5.0 mg) was added to a solution of (3-oxo-2-(pent-2-yn-1-yl)cyclopentyl)acetic acid methyl ester (**2a**) (0.10 g, 0.4 mmol) in toluene (10 ml). The system was evacuated and refilled with hydrogen gas via a balloon attached to the flask. The mixture was stirred under this hydrogen atmosphere for 3 h at room temperature before it was filtered through a short plug of kieselguhr which was then washed thoroughly with Et_2O. The filtrate was evaporated under reduced pressure to give *cis*-methyl jasmonate (**1a**) (0.10 g, 99%) as a pale yellow oil. This sample was indistinguishable in its IR- and ^{1}H-NMR spectra from a redistilled commercial sample [19]. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 0.94$ (3H, t, $J = 7.2$ Hz, CH_3CH_2), 1.51 (1H, m), 1.89 (1H, m), 2.00–2.39 (9H, overlapping m), 2.70 (1H, m), 3.69 (3H, s, OCH_3), 5.25 (1H, m, olefinic-H), 5.46 (1H, m, olefinic-H). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 14.6$, 21.0, 25.8, 27.6, 38.1, 38.4, 39.2, 52.0, 54.4, 125.3 (olefinic-C), 134.4 (olefinic-C), 172.9 (CO_2), 219.4 (CO). ν_{max} (cm^{-1}, CH_2Cl_2): 1740. *T_2-cis-methyl jasmonate* (**1b**): ^{3}H-NMR (320 MHz, $CDCl_3$): $\delta = 5.30$ (olefinic-T), 5.48 (olefinic-T).

4.10. (5-Oxocyclopent-1-en-1-yl)acetaldehyde [2-(formylmethyl)cyclopent-2-en-1-one] (9b) [20]

The Dess–Martin periodinane [13] (6.30 g, 14.8 mmol) was added to a solution of 2-(2-hydroxyethyl)-cyclopent-2-en-1-one (**9a**) [4a] (1.60 g, 13.0 mmol) in 10% MeCN in CH_2Cl_2 (50 ml) at 25 °C. The mixture was stirred for 1 h before aqueous sodium thiosulfate solution (14.9 g in 30 ml) and saturated aqueous sodium hydrogen carbonate solution (50 ml) was added. The mixture was stirred vigorously for a further 30 min before the organic phase was separated, dried, and concentrated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using 50% Et_2O in light petroleum as the eluent to give (5-oxocyclopent-1-en-1-yl)-acetaldehyde (**9b**) (0.80 g, 50%) as a pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 2.42$ (2H, m, CH_2CH_2CO), 2.66 (2H, m, CH_2CH_2CO), 3.33 (2H, s, $=CCH_2CHO$), 7.58 (1H, m, HC=), 9.68 (1H, s, CHO). ν_{max} (cm^{-1}, CH_2Cl_2): 2927, 2844, 2736, 1727, 1695.

4.11. 2-(Methanesulfonyloxymethyl)cyclopent-2-en-1-one (9g)

A solution of methanesulfonyl chloride (0.69 g, 6.03 mmol) in CH_2Cl_2 (10 ml) was added over a 5 min period to a stirred solution of 2-(hydroxymethyl)-cyclopent-2-en-1-one (**9d**) [4a] (0.52 g, 4.64 mmol) and Et_3N (1.00 g, 9.90 mmol) in CH_2Cl_2 (10 ml) at −5 °C. The mixture was then stirred for 1 h before it was filtered through a pad of silica using CH_2Cl_2 as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using Et_2O as the eluent to give *2-(methanesulfonyloxymethyl)cyclopent-*

2-en-1-one (**9g**) (0.79 g, 90%) as a clear oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 2.42$ (2H, m, CH_2CO), 2.66 (2H, m, CH_2CH=), 3.03 (3H, s, CH_3SO_3), 4.81 (2H, m, CH_2O), 7.74 (1H, s, CH=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = 27.3$, 34.7, 37.7, 63.1 (CH_2O), 139.4 (OC=), 163.5 (HC=), 207.2 (C=O). ν_{max} (cm^{-1}, CH_2Cl_2): 1734, 1695, 1625. Compound instability prevented any further characterisation.

4.12. 2-(Iodomethyl)cyclopent-2-en-1-one (9h)

A solution of 2-(methanesulfonyloxymethyl)cyclopent-2-en-1-one (**9g**) (1.00 g, 5.26 mmol) and sodium iodide (1.30 g, 8.67 mmol) in acetone (50 ml) was heated under reflux for 4 h. The mixture was filtered and the filtrate was concentrated under reduced pressure to give *2-(iodomethy)cyclopent-2-en-1-one* (**9h**) (1.05 g, 90%) as a yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$): $\delta = 2.41$ (2H, m, CH_2CO), 2.52 (2H, m, CH_2CH=), 3.88 (2H, s, CH_2I), 7.96 (1H, s, HC=). ^{13}C-NMR (100 MHz, $CDCl_3$): $\delta = -8.1$ (CH_2I), 26.9, 35.0, 144.0 (OC=), 161.2 (HC=), 206.7 (C=O). ν_{max} (cm^{-1}, CH_2Cl_2): 1701, 1631. HRMS: m/z: Found: 221.95327. Calc. for C_6H_7IO [M^+]: 221.95417.

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[7] Surprisingly, the use of vinyl acetate, in place of the benzoate, with complex **4a** afforded the unreduced cyclopentenone, 5-acetoxy-2-(pent-2-yn-1-yl)cyclopent-2-en-1-one (13% yield), as the main isolable product; see Section 4.

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