Total synthesis of the monoterpenoid alkaloid (±)-tangutorine†

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A novel approach to a formal total synthesis of the monoterpenoid indole alkaloid (±)-tangutorine has been developed starting from an α,β-unsaturated cyclic dehydroamino ester. Synthesis of the rather unusual trans-substituted 2,3-indoloquinolizidine substructure was accomplished via Cu(II)-mediated conjugate addition and organozinc/copper coupling as the key steps, thereby setting the stage for ring-closing metathesis to produce the quinolone substructure. Finally, Bischler–Napieralski cyclization gave rise to the pentacyclic system of (±)-tangutorine thereby realizing a formal synthesis in an overall yield of 5.2% in eight consecutive steps.

Introduction

Monoterpenoid alkaloids are widespread in nature and possess diverse structures with often relevant biological properties.1 β-Carbolines (e.g. 1–3, Fig. 1) belong to this class and form one of the principal alkaloid groups in nature that are biosynthetically derived from tryptophan.2 This class contains some of the most important alkaloids used in medicine such as reserpine (3).3 In 1999, a novel racemic β-carboline named tangutorine (1) was isolated by Duan and colleagues from the leaves of the Chinese medical plant Nitraria tangutorine.4 Although tangutorine (1) is structurally related to the more common yohimbine skeleton (viz. 2), it is the only known β-carboline alkaloid containing an indoloquinolizidine substructure.

Tangutorine (1) shows interesting biological effects on the regulation of cell cycle and cellular morphology and therefore might serve as a lead compound for the design of new drugs.5 Since its isolation in 1999, several syntheses of (±)-tangutorine (1) have been published,6–10 one of which describes the synthesis of both optical antipodes.11 Following-up on previously developed methodology from our group on ring-closing metathesis (RCM) of (sterically hindered) enamides,12,13 and its application in the synthesis of substituted piperidines,14,15 we herewith describe a novel approach to racemic tangutorine (1) starting from key building block 7.16 As depicted in Scheme 1, a first disconnection of the pentacyclic...
tangutorine framework would involve a Bischof–Napieralski cyclization, followed by reduction giving rise to bicyclic precursor 4. Subsequently, hexahydroquinolone 4 could be derived via RCM from the trans-5,6-disubstituted lactam 5. We were hopeful that the primary iodide 6 would serve as a suitable precursor to deliver 5 via organozinc/copper-mediated coupling with ethyl 2-(bromomethyl)acrylate. Finally, diastereoselective copper-catalyzed 1,4-addition onto 7, followed by some further functionalization was anticipated to lead to iodide 6.

Results and discussion

Recently, we have shown that the unsaturated lactam 7 can be readily prepared from a linear enamide precursor through RCM.15 Having lactam 7 thus available, diastereoselective copper-catalyzed 1,4-addition of vinylmagnesium bromide in the presence of CuI at −20 °C provided the trans-5,6-disubstituted lactam 8 in 72% yield as a single diastereoisomer (Scheme 2).15 Next, conversion of the ester functionality into the corresponding primary iodide was aimed to provide a handle for introduction of the second double bond, thereby setting the stage for RCM formation of the second ring. Disappointingly, reduction with DIBAL-H at −78 °C was unproductive, and starting material was recovered. Use of LiAlH₄ also gave no product, but instead led to reduction of both the alcohol and the amide. Gratifyingly, reduction with LiEt₃BH at 0 °C was efficient and yielded the desired alcohol 9 in 88%. Subsequent conversion into primary iodide 6 was accomplished with iodine in the presence of triphenylphosphine and imidazole in 78% yield. To prepare RCM precursor 10, initially Grignard-mediated substitution of the iodide and the corresponding tosylate was investigated. In either case, however, no reaction was observed and only starting material was recovered. We then turned to an organozinc/copper coupling strategy to introduce the second olefin (Scheme 2).16 Reaction of iodide 6 with activated zinc and ethyl 2-(bromomethyl)acrylate did result in the desired RCM-precursor 10 in 42% yield together with the undesired ring-opened product 11 (39%).

Scheme 2 Organozinc/copper coupling strategy.

Having RCM-precursor 10 in hand, treatment with the Grubbs’ second generation catalyst (G2, 10 mol%, toluene, 80 °C) led to hexahydroquinolone 12 in 89% yield (Scheme 3). To introduce the indole moiety, we initially turned to N-alkylation of quinolizidine 12 with Boc-protected tryptophyl bromide (14). To this end, the amide group had to be deprotected. PMB-deprotection of 12 proved to be somewhat less trivial than expected, however. Oxidation with ceric ammonium nitrate (CAN) in MeCN led to long reaction times despite using a large excess of reagents, eventually resulting in multiple products. Alternatively, treatment with DDQ in H₂O/CH₂Cl₂ mixtures did not show any conversion at all. Treatment with TFA at elevated temperatures on the other hand proceeded smoothly resulting in 13 in 72% yield. Unfortunately, alkylation of lactam 13 with bromide 14 and DIPEA at elevated temperature only resulted in degradation of the starting material.19 Disappointingly, reaction with sodium hydride in DMF in the presence of 14 (and additional TBAI or KI) did not lead to any product either.

Introduction of the indole group was therefore envisioned to occur starting from the cyclic dehydroamino ester 7 (Scheme 4). PMB-deprotection of 7 using TFA yielded lactam 15 in 85% yield.

Scheme 3 Toward quinolone precursor 5.

Scheme 4 Bischof–Napieralski cyclization.
Alkylation with Boc-protected tryptophyl bromide (14) in the presence of sodium hydride now resulted in the desired N-alkylated product, but the isolated yield never exceeded 10%. When sodium hydride was added portionwise (5 times 0.25 equiv) the yield was raised to an acceptable 53%. With 16 successfully synthesized, trans-selective 1,4-addition with vinylmagnesium bromide, followed by Bischler–Napieralski cyclization was thought to lead to the desired pentacycle.26 Indeed, diastereoselective conjugate addition, and subsequent treatment of 17 with POCl₃ in DMF at elevated temperatures led to iminium-salt 18, which was then reduced with sodium borohydride in ethanol to give an inseparable mixture of diastereoisomers 19 (86 : 14). Unfortunately, the Boc-group was cleaved during the cyclization so that reprotection was necessary to complete the synthesis.

To avoid the reprotection step, a slightly different strategy was pursued, in which the quinolizidine substructure was constructed from dehydroamino ester 17 in four consecutive steps (Scheme 5). The reduction/iodination protocol first yielded iodide 21 in 69% yield over two steps. Then, the organozinc/copper coupling afforded RCM precursor 5 in a moderate yield of 52%, again together with the undesired 1,4-diene (34%) as described previously. Finally, RCM proceeded uneventfully to give quinolone structure 4 in a near quantitative conversion. En route to completion of the synthesis, pentacycle 23 was produced in diastereomerically pure form via Bischler–Napieralski cyclization of lactam 4. Surprisingly, the Boc-group was only partially removed during this reaction. Separation of both products and subsequent Boc-deprotection of 22 with TFA resulted in the known carboxylic ester 23 in an overall yield of 45%. Its spectral data were in agreement with values reported in literature.4

Conclusions
In conclusion, we have demonstrated the synthetic value of the dehydroamino ester building block 7 through application in the synthesis of (±)-tangutorine in eight consecutive steps in an overall yield of 5.2%. The pathway is characterized by a diastereoselective copper-catalyzed 1,4-addition onto the cyclic dehydroamino ester, an organozinc/copper coupling followed by ring-closing metathesis of the diolefin for the construction of the quinolone substructure and a diastereoselective Bischler–Napieralski cyclization.

Experimental

General

1H-NMR spectra were recorded on a 400 MHz NMR spectrometer. 13C-NMR spectra were recorded on a 75 MHz NMR spectrometer. Chemical shifts (δ) are reported in ppm and relative to a residual solvent peak (1H-NMR: 7.26 in CDCl₃, 13C-NMR: 77.0 in CDCl₃). IR spectra were recorded on an ATR IR-spectrometer. Rf values are obtained using thin layer chromatography (TLC) on silica gel-coated plates with the indicated eluents and compounds were detected with UV-light, potassium permanganate, p-anisaldehyde or ninhydrin.

1-[2-((1-tert-Butyloxycarbonyl-1-H-indol-3-yl)ethyl]-2-oxo-1,2,3, 4,4a,5,6,8a-octahydroquinoline-7-carboxylic acid ethyl ester (4)

Compound 5 (28 mg, 0.056 mmol) was dissolved in toluene (1 mL) and argon was flushed through the solvent. The second generation Grubbs’ catalyst (5 mg, 0.03 mmol) was added and the solution was heated to 80 °C. After 1 h, the solution was cooled to room temperature and concentrated in vacuo. The residue was purified by flash column chromatography (EtOAc/heptane 1:1) affording compound 4 (26 mg, 98%) as a colorless oil. Rf 0.38 (EtOAc/heptane 2:1). FTIR (ATR) 2922, 1728, 1639, 1450, 1369, 1256, 1157 cm⁻¹. 1H NMR (CDCl₃, 400 MHz): δ 8.12 (d, J = 7.0 Hz, 1H), 7.69 (d, J = 7.2 Hz, 1H), 7.43 (s, 1H), 7.35–7.22 (m, 2H), 6.70 (d, J = 1.1 Hz, 1H), 4.21 (q, J = 6.9 Hz, 2H), 3.84–3.68 (m, 2H), 2.83–2.73 (m, 1H), 2.69–2.53 (m, 3H), 2.46–2.36 (m, 2H), 2.34–2.23 (m, 1H), 2.04–1.96 (m, 1H), 1.67 (s, 9H), 1.63–1.50 (m, 2H), 1.31 (t, J = 7.1 Hz, 3H). 13C NMR (CDCl₃, 300 MHz): δ 170.2, 166.1, 149.3, 138.7, 135.0, 130.0, 129.7, 128.5, 127.7, 124.8, 120.4, 122.4, 122.1, 118.7, 117.5, 114.8, 83.0, 60.2, 58.1, 42.3, 39.6, 32.6, 32.5, 27.8, 26.8, 26.0, 24.1, 23.7, 13.8. HRMS (ESI) m/z calcd for C₂₇H₃₄N₂O₅ (M + Na)⁺: 489.2368, found: 489.2365.

3-[2-[(3-Ethoxy carbonylbut-3-enyl)-6-oxo-3-vinylpiperidin-1-yl]ethyl] indole-1-carboxylic acid tert-butyl ester (5)

Zinc dust (42 mg, 0.65 mmol) was weighed into a Schlenk flask, which was flame dried and flushed with argon. 1,2-Dibromoethane (2.8 µL, 0.03 mmol) in dry DMF (0.2 mL) was added and the flask was heated to 60 °C for 1 h. Me₂SiCl (0.41 µL, 0.0031 mmol) was added and the mixture was stirred at 60 °C for 30 min.
Compound 21 (55 mg, 0.11 mmol) was dissolved in DMF (0.3 mL), added to the mixture and stirred for 10 min at 60 °C. CuCN (10 mg, 0.11 mmol) and LiCl (9.2 mg, 0.22 mmol) were heated to 150 °C under vacuum for 2 h and cooled to room temperature. Addition of DMF (0.3 mL) formed a soluble CuCN-LiCl complex. After cooling, the organozinc reagent was cooled to −55 °C, the Cu-complex was added and the solution was warmed to 0 °C. After stirring for 10 min at 0 °C, the solution was cooled to −55 °C and ethyl 2-(bromomethyl)acrylate (18.2 μL, 0.13 mmol) was added. The solution was slowly warmed to room temperature and stirred overnight. The mixture was filtered over Celite, diluted with EtOAc (10 mL), washed with aqueous NH4Cl (50 mL) and brine (50 mL), dried (MgSO4, 0.46 mmol) was added. After 30 min the reaction was cooled to 0 °C and ethyl 2-(bromomethyl)acrylate (18.2 μL, 0.13 mmol) was added. The reaction was heated to 70 °C and stirred for 1 h. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording lactam 6 (43 mg, 42%) as a viscous oil. 6-Hydroxymethyl-1-(4-methoxybenzyl)-2-oxo-5-vinylpiperidine (9) was extracted with CH2Cl2 (2 × 40 mL), dried over MgSO4 and concentrated in vacuo. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) to obtain compound 9 (80 mg, 0.16 mmol) as a white solid. FTIR (ATR) 3376, 2940, 1712, 1635, 1245 cm−1. 1H NMR (CDCl3, 400 MHz): δ 7.16 (d, J = 8.4 Hz, 2H), 6.86 (d, J = 8.7 Hz, 2H), 5.59–5.49 (m, 1H), 5.51 (d, J = 15.0 Hz, 1H), 5.14–5.04 (m, 2H), 3.80 (s, 3H), 3.75 (d, J = 15.1 Hz, 1H), 3.36–3.33 (m, 2H), 2.94–2.89 (m, 1H), 2.68–2.60 (m, 1H), 2.60–2.41 (m, 2H), 1.95–1.86 (m, 1H), 1.78–1.66 (m, 1H). 13C NMR (CDCl3, 75 MHz): δ 169.9, 158.6, 137.8, 129.1, 127.9, 116.9, 113.7, 57.8, 54.8, 45.4, 41.4, 30.0, 23.2, 9.4. HRMS (ESI) m/z calcd for C16H20INO2Na (M + Na)+: 408.0439, found: 408.0436.

1-(4-Methoxybenzyl)-6-oxo-3-vinylpiperidine-2-carboxylic acid ethyl ester (8)

To a cooled solution (−30 °C) of CuI (3.15 g, 16.6 mmol) in Et2O (30 mL), a 1 M vinminium bromide solution in THF (8.3 mL, 8.3 mmol) was added. The solution was stirred for 20 min and was cooled to −70 °C. Then compound 7 (1.20 g, 4.15 mmol) dissolved in Et2O (10 mL) was added and the temperature was slowly warmed to −10 °C. The reaction was quenched with 0.1 M HCl and was washed with aqueous Na2SO3 (2 × 40 mL), NaHCO3, (40 mL) and H2O (40 mL), dried over MgSO4, and concentrated in vacuo. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording compound 8 (0.95 g, 72%) as a viscous oil. FTIR (ATR) 2940, 1738, 1649, 1511 cm−1. 1H NMR (CDCl3, 400 MHz): δ 7.16 (d, J = 8.6 Hz, 2H), 6.84 (d, J = 8.7 Hz, 2H), 5.69–5.59 (m, 1H), 5.53 (d, J = 7.4 Hz, 1H), 5.08–4.91 (m, 2H), 4.22–4.12 (m, 2H), 3.89 (dd, J = 3.9, 1.0 Hz, 1H), 3.79 (s, 3H), 3.69 (d, J = 14.7, 1H), 2.83–2.77 (m, 1H), 2.54–2.47 (m, 2H), 2.00–1.90 (m, 1H), 1.78–1.71 (m, 1H), 1.26 (t, J = 7.1 Hz, 3H). 13C NMR (CDCl3, 75 MHz): δ 170.9, 169.3, 158.7, 136.2, 129.8, 127.9 116.3, 113.4, 61.9, 61.2548, 48.1 38.6 28.3 22.9 13.7. HRMS (ESI) m/z calcd for C16H20INO2Na (M + Na)+: 340.1537, found: 340.1525.

4-[1-(4-Methoxybenzyl)-6-oxo-3-vinylpiperidin-2-yl]-2-methylenebutyric acid ethyl ester (10)

Zinc dust (52.3 mg, 0.81 mmol) was weighed into a Schlenk flask, which was evacuated under flame drying and flushed with argon. 1,2-Dibromoethane (3.3 μL, 0.04 mmol) in dry DMF (0.3 mL) was added and the flask was heated to 60 °C for 1 h. MtSCI (0.5 μL, 0.004 mmol) was added and the mixture was stirred at 60 °C for 30 min. Compound 6 (50 mg, 0.13 mmol) was dissolved in DMF (0.4 mL), added to the mixture and stirred for 10 min at 60 °C. CuCN (11.6 mg, 0.13 mmol) and LiCl (11 mg, 0.26 mmol) were heated to 150 °C under vacuum for 2 h and cooled to room temperature. Addition of DMF (0.5 mL) formed a soluble CuCN-LiCl complex. After cooling the organozinc reagent to −55 °C the Cu-complex was added and the solution was warmed to 0 °C. After stirring for 10 min at 0 °C the solution was cooled to −55 °C and ethyl 2-(bromomethyl)acrylate (21.8 μL, 0.156 mmol) was added. The solution was slowly warmed to room temperature and stirred for 16 h. The mixture was filtered over celite, diluted with EtOAc, washed with aqueous NH4Cl and brine, dried over MgSO4 and concentrated in vacuo. The residue was purified by flash column chromatography (EtOAc/heptane 1:1) affording compound 10 (43 mg, 42%) as a viscous oil. FTIR (ATR) 2936, 1712, 1635, 1512, 1245 cm−1. 1H NMR (CDCl3, 400 MHz): δ 7.18 (d, J = 8.6 Hz, 2H), 6.83 (d, J = 8.7 Hz, 2H), 6.16 (d, J = 1.2 Hz, 1H), 5.60–5.50 (m, 1H),
5.50 (d, J = 1.2 Hz, 1H), 5.42 (d, J = 14.6 Hz, 1H), 5.01–4.92 (m, 2H), 4.23 (q, J = 7.1 Hz, 2H), 3.79 (s, 3H), 3.76 (d, J = 14.6 Hz, 1H), 3.18–3.13 (m, 1H), 2.58–2.45 (m, 2H), 2.44–2.34 (m, 1H), 2.33–2.17 (m, 2H), 2.06–1.95 (m, 1H), 1.90–1.63 (m, 3H), 1.32 (t, J = 7.1 Hz, 3H). \(^{1}C\) NMR (CDCl\(_3\), 75 MHz): \(\delta\) 169.7, 166.3, 158.4, 139.4, 138.4, 129.4, 128.9, 115.6, 113.4, 60.3, 58.0, 54.8, 46.0, 39.3, 30.1, 28.9, 27.5, 22.5, 13.8. HRMS (ESI) \(m/z\) calcd for \(\text{C}_2\text{H}_3\text{NO}_2\text{Na (M + Na)}^+\): 394.1997, found: 394.1994.

### 4-Vinlyhex-5-enic acid 4-methoxybenzylamide (11)

Compound 11 (31 mg, 46%) was isolated as a side product from the organozinc/copper coupling with compound 6. To a cooled solution (9.2 mg, 0.01 mmol) was added and the solution was heated to 80 °C. After 1 h, the solution was cooled to room temperature and concentrated in vacuo.

### 1-(4-Methoxybenzyl)-2-oxo-1,2,3,4,4a,7,8,8a-octahydroquinoline-6-carboxylic acid ethyl ester (12)

Compound 10 (40 mg, 0.11 mmol) was dissolved in toluene (4 mL) and argon was flushed through the solvent. The second generation Grubbs’ catalyst (9.2 mg, 0.01 mmol) was added and the solution was heated to 80 °C. After 1 h, the solution was cooled to room temperature and concentrated in vacuo.

### 3-[2-(6-Ethoxycarbonyl-2-oxo-3,4-dihydro-2H-pyridin-1-yloyl)indole-1-carboxylic acid tert-butyl ester (16)

To a cooled solution (≈30 °C) of CuI (0.3 g, 1.75 mmol) in Et\(_2\)O (2 mL), a 1 M vinylmagnesium bromide solution in THF (0.87 mL, 0.87 mmol) was added. The solution was stirred for 20 min and cooled to −70 °C. Then compound 16 (120 mg, 0.29 mmol) dissolved in Et\(_2\)O (1 mL) was added and the solution was slowly warmed to −10 °C. The reaction was stirred with Et\(_2\)O and quenched with 0.1 M HCl (10 mL), washed with aqueous Na\(_2\)SO\(_4\) (2 × 10 mL), NaHCO\(_3\) (10 mL) and H\(_2\)O (10 mL), dried over MgSO\(_4\) and concentrated in vacuo.

### 1-[2-(6-Ethoxycarbonyl-6-oxo-3-vinylpiperidin-1-yl)ethyl]indole-1-carboxylic acid tert-butyl ester (17)

To a cooled solution (≈30 °C) of CuI (0.3 g, 1.75 mmol) in Et\(_2\)O (2 mL), a 1 M vinylmagnesium bromide solution in THF (0.87 mL, 0.87 mmol) was added. The solution was stirred for 20 min and cooled to −70 °C. Then compound 16 (120 mg, 0.29 mmol) dissolved in Et\(_2\)O (1 mL) was added and the solution was slowly warmed to −10 °C. The reaction was stirred with Et\(_2\)O and quenched with 0.1 M HCl (10 mL), washed with aqueous Na\(_2\)SO\(_4\) (2 × 10 mL), NaHCO\(_3\) (10 mL) and H\(_2\)O (10 mL), dried over MgSO\(_4\) and concentrated in vacuo.

### 6-Oxo-1,4,5,6-tetrahydropyridine-2-carboxylic acid ethyl ester (15)

Compound 7 (1.04 g, 3.6 mmol) was dissolved in a TFA/CH\(_2\)Cl\(_2\) mixture (1:4, 36 mL) and stirred overnight at 50 °C. The reaction was quenched with NaHCO\(_3\) and the organic compound was extracted with CH\(_2\)Cl\(_2\) (2 × 40 mL), dried over Na\(_2\)SO\(_4\) and concentrated in vacuo.

### 3-Vinyl-1,2,3,4,6,7,12b-octahydropyridino[2,3-a]quinolizine-4-carboxylic acid ethyl ester (19)

Compound 17 (20 mg, 0.045 mmol) was dissolved in toluene (1 mL) and POCl\(_3\) (42 µL, 0.45 mmol) was added. The solution was stirred at 70 °C for 2 h. The reaction was concentrated under reduced pressure, the residue was dissolved in EtOH (1 mL) and cooled to 0 °C. NaBH\(_4\) (3.4 mg, 0.09 mmol) was added and the reaction was stirred for 10 min at 0 °C, diluted with CH\(_2\)Cl\(_2\) (10 mL) and quenched with aqueous NaHCO\(_3\).
3-[(2-Hydroxymethyl-6-oxo-3-vinylpiperidin-1-yl)ethyl]indole-1-carboxylic acid tert-butylox ester (20)

To a cooled solution (0 °C) of compound 17 (93 mg, 0.21 mmol) in THF (2.5 mL) LiEt₂BH (0.63 mL, 0.63 mmol, 1 M solution in THF) was added. After stirring for 2.5 h at 0 °C, the reaction was quenched with ice-water (25 mL) and the product was extracted with CH₂Cl₂ (2 x 40 mL), dried over MgSO₄ and concentrated in vacuo. The residue was purified by flash chromatography (EtOAc/heptane 1:1 affording compound 20 (74 mg, 88%) as a viscous oil. Rₜ, 0.35 (CHCl₃/MeOH 9:1). FTIR (ATR) 3322, 1731, 1615, 1455, 1370 cm⁻¹.¹H NMR (CDCl₃, 7.5M H₂), δ: 7.69 (br s, 1H), 7.46 (d, J = 7.8 Hz, 1H), 7.30 (d, d = 7.7 Hz, 1H), 7.11 (dd, J = 15.9, 7.1, 1.2 Hz, 2H), 5.68 (m, 1H), 5.04 (dd, d = 10.2, 1.7 Hz, 1H), 4.30-4.20 (m, 2H), 3.40 (br d, J = 11.4 Hz, 1H), 3.06-2.97 (m, 2H), 2.95 (d, J = 10.3 Hz, 1H), 2.76-2.68 (m, 1H), 2.68-2.54 (m, 2H), 2.19-2.11 (m, 1H), 2.03-1.96 (m, 1H), 1.87-1.75 (m, 1H), 1.56-1.44 (m, 1H), 1.30 (t, J = 7.1 Hz, 3H), 1.13-0.83 (m, 1H), 0.83-0.73 (m, 1H). ¹³C NMR (CDCl₃, 75 MHz): δ: 167.7, 137.9, 135.5, 135.5, 121.0, 119.0, 117.7, 116.1, 110.2, 108.0, 105.7, 72.6, 60.3, 58.8, 50.7, 44.9, 29.7, 28.3, 21.4, 13.9. HRMS (ESI) m/z calcd for C₁₃H₁₄N₂O₄ (M + H⁺): 275.1198, found: 275.1191.

2,4a,5,6,11b,12,13,13a-Octahydro-1H-4b,11-diazainedeno[2,1-alphenanthrene-3,11-di-carboxylic acid 11-tert-butylox ester 3-ethyl ester (22)

Compound 4 (26 mg, 0.056 mmol) was dissolved in toluene (1 mL) and POCl₃ (52 μL, 0.56 mmol) was added. The solution was stirred at 70 °C for 2 h, after which additional POCl₃ (27 μL, 0.27 mmol) was added and stirring was continued for another hour at 70 °C. The reaction was concentrated under reduced pressure, the residue was dissolved in EtOH (1 mL) and cooled to 0 °C. NaBH₄ (4.2 mg, 0.11 mmol) was added, the reaction was stirred for 10 min at 0 °C, diluted with CH₂Cl₂ (50 mL) and quenched with aqueous NaHCO₃ (50 mL). The organic layer was extracted, dried (MgSO₄) and concentrated in vacuo. The residue was purified by flash column chromatography (EtOAc/heptane 1:2 affording compound 22 (11.5 mg, 46%) as a viscous oil. Rₜ, 0.63 (EtOAc/heptane 2:1). FTIR (ATR) 2933, 1725, 1477, 732 cm⁻¹.¹H NMR (CDCl₃, 400 MHz): δ: 8.16 (d, J = 9.0 Hz, 1H), 7.41 (d, J = 11.2 Hz, 1H), 7.29-7.19 (m, 2H), 6.70 (s, 1H), 4.51 (d, J = 10.9 Hz, 1H), 4.21 (q, J = 7.2 Hz, 2H), 3.08-2.95 (m, 2H), 2.87-2.71 (m, 2H), 2.62 (dd, J = 15.8, 4.2 Hz, 1H), 2.39 (t, J = 10.7 Hz, 2H), 2.10-1.97 (m, 3H), 1.90-1.76 (m, 2H), 1.65 (s, 9H), 1.53-1.40 (m, 1H), 1.31 (t, J = 7.1 Hz, 3H).¹³C NMR (CDCl₃, 75 MHz): δ: 166.9, 149.6, 141.6, 136.4, 136.0, 129.4, 128.8, 123.4, 121.7, 117.4, 115.3, 114.5, 83.1, 63.3, 60.0, 58.2, 53.3, 33.8, 30.8, 27.8, 26.8, 25.3, 22.1, 13.8. HRMS (ESI) m/z calcd for C₂₇H₃₄N₂O₄ [M + Na]⁺: 541.2599, found: 541.2597.

2,1,4,5,6,11b,12,13,13a-Decahydro-4b,11-diazainedeno[2,1-alphenanthrene-3,11-di-carboxylic acid ethyl ester (23)

Compound 23 (4 mg, 20%) was isolated as a side product of the Bischer-Napierski reaction with compound 4. Rₜ, 0.54 (EtOAc/heptane 2:1). FTIR (ATR) 2919, 1700, 1648, 1255, 736 cm⁻¹.¹H NMR (CDCl₃, 400 MHz): δ: 7.70 (s, 1H), 7.39 (d, J = 7.9 Hz, 2H), 7.21 (d, d = 7.9 Hz, 2H), 7.16-7.06 (m, 2H), 6.68 (s, 1H), 4.21 (q, J = 7.2, 7.1 Hz, 2H), 3.62 (dd, d = 10.4, 4.8, 2.1 Hz, 1H), 3.48 (d, d = 11.4 Hz, 1H), 2.98-2.88 (m, 1H), 2.79 (d, J = 15.5 Hz, 1H), 2.62 (dd, d = 16.1, 5.2 Hz, 1H), 2.45-2.27 (m, 4H), 2.25-2.14 (m, 2H), 2.09-2.02 (m, 1H), 1.82 (dq, d = 12.2, 3.6 Hz, 1H), 1.62-1.33 (m, 3H), 1.31 (t, J = 7.1 Hz, 3H).¹³C NMR (CDCl₃, 75 MHz): δ: 167.2, 141.6, 136.0, 135.1, 129.5, 127.3, 121.4, 119.4, 118.2, 110.7, 108.4, 64.0, 60.5, 64.5, 47.0, 40.7, 30.3, 30.0, 26.0, 25.0, 22.1, 14.3. HRMS (ESI) m/z calcd for C₁₃H₁₄N₂O₂ [M + H⁺]: 351.2074, found: 351.2073.

Deprotection of 2,4a,5,6,11b,12,13,13a-octahydro-1H-4b,11-diazainedeno[2,1-alphenanthrene-3,11-di-carboxylic acid 11-tert-butylox ester 3-ethyl ester (23)

Compound 22 (28 mg, 0.056 mmol) was dissolved in a mixture of TFA/CH₂Cl₂ (1:4) and stirred at room temperature. After 64 h the solution was concentrated in vacuo. The residue was purified by flash column chromatography (EtOAc/heptane 1:1) affording compound 23 (13 mg, 55%). Rₜ, 0.21 (EtOAc/heptane 1:1).
Notes and references