

PDF hosted at the Radboud Repository of the Radboud University Nijmegen

The following full text is a publisher's version.

For additional information about this publication click this link.

<http://hdl.handle.net/2066/94149>

Please be advised that this information was generated on 2021-03-03 and may be subject to change.

Total synthesis of the monoterpene indole alkaloid (\pm)-tangutorine†

Sebastiaan (Bas) A. M. W. van den Broek, Jaap G. H. Lemmers, Floris L. van Delft and Floris P. J. T. Rutjes*

Received 7th September 2011, Accepted 10th November 2011

DOI: 10.1039/c1ob06539d

A novel approach to a formal total synthesis of the monoterpene indole alkaloid (\pm)-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 (\pm)-tangutorine thereby realizing a formal synthesis in an overall yield of 5.2% in eight consecutive steps.

Introduction

Monoterpene 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 (\pm)-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

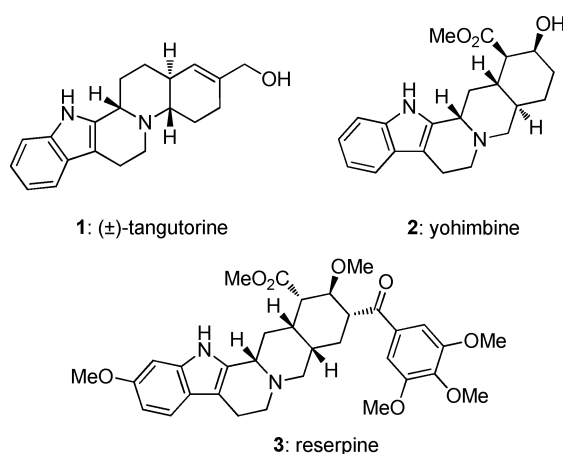
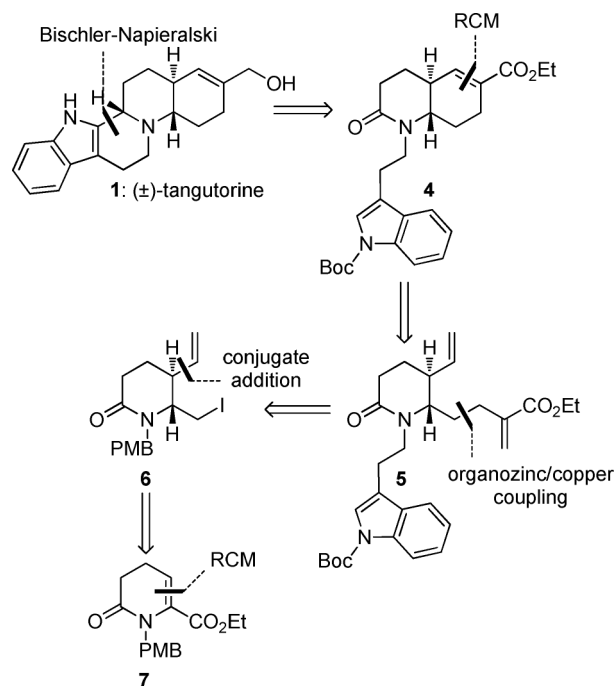


Fig. 1 Monoterpene indole alkaloids.

Scheme 1 Retrosynthesis of (\pm)-tangutorine (**1**).

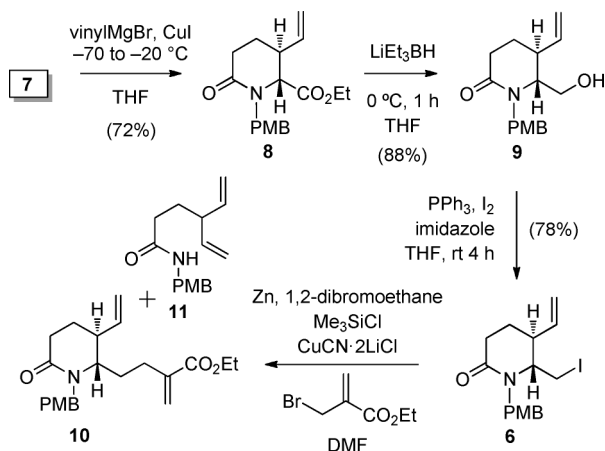
Radboud University Nijmegen, Institute for Molecules and Materials, Heyendaalseweg 135, NL-6525 AJ Nijmegen, The Netherlands. E-mail: F.Rutjes@science.ru.nl

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c1ob06539d

tangutorine framework would involve a Bischler–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**.

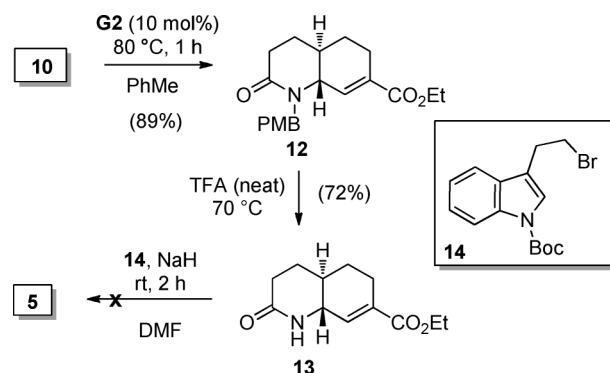
Results and discussion

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 $-20\text{ }^{\circ}\text{C}$ provided the *trans*-5,6-disubstituted lactam **8** in 72% yield as a single diastereoisomer (Scheme 2).¹⁷ 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 $-78\text{ }^{\circ}\text{C}$ was unproductive, and starting material was recovered. Use of LiAlH_4 also gave no product, but instead led to reduction of both the alcohol and the amide. Gratifyingly, reduction with LiEt_3BH at $0\text{ }^{\circ}\text{C}$ 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).¹⁸ 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.

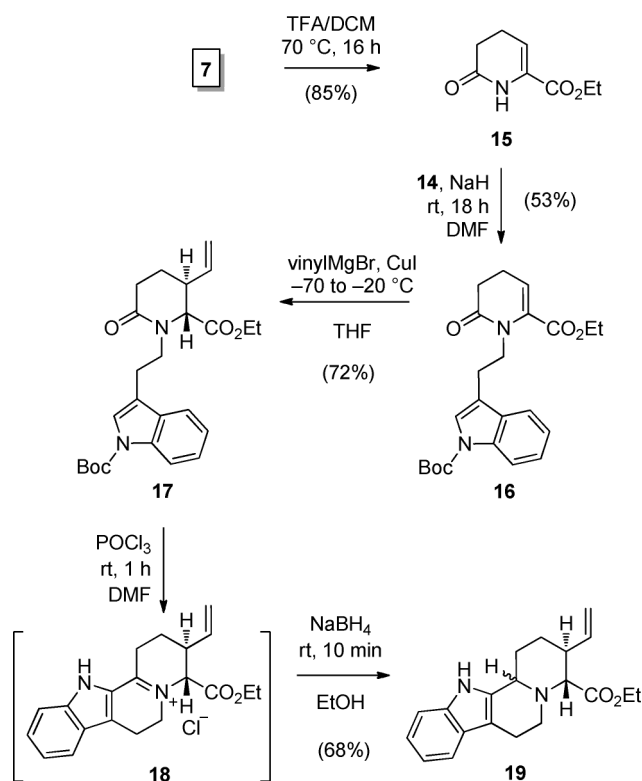
Having RCM-precursor **10** in hand, treatment with the Grubbs' second generation catalyst (**G2**, 10 mol%, toluene, $80\text{ }^{\circ}\text{C}$) led to hexahydroquinolone **12** in 89% yield (Scheme 3). To introduce the indole moiety, we initially turned to *N*-alkylation of quinolizidine



Scheme 3 Toward quinolone precursor **5**.

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 $\text{H}_2\text{O}/\text{CH}_2\text{Cl}_2$ 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 4 Bischler–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.²⁰ 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 re-protection was necessary to complete the synthesis.

To avoid the re-protection 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

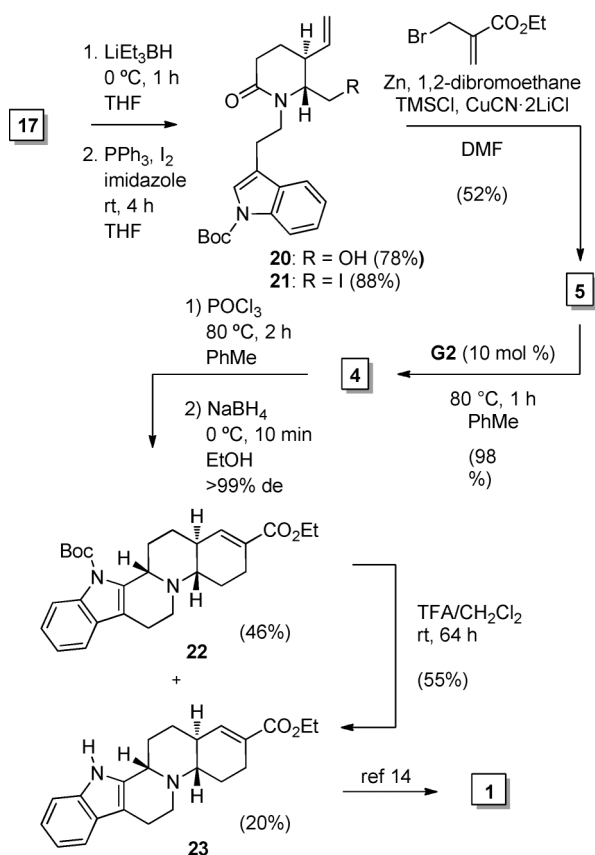
¹H-NMR spectra were recorded on a 400 MHz NMR spectrometer. ¹³C-NMR spectra were recorded on a 75 MHz NMR spectrometer. Chemical shifts (δ) are reported in ppm and relative to a residual solvent peak (¹H-NMR: 7.26 in CDCl₃, ¹³C-NMR: 77.0 in CDCl₃). IR spectra were recorded on an ATR IR-spectrometer. *R_f* 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*-Butoxycarbonyl-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, 0.005 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. *R_f* 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), 3.14 (ddd, *J* = 12.1, 9.7, 2.2 Hz, 1H), 3.09–3.00 (m, 1H), 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, 124.0, 122.4, 122.1, 118.7, 117.5, 114.8, 83.0, 60.2, 58.1, 42.3, 39.6, 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-[2-(3-Ethoxycarbonylbut-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 μ L, 0.03 mmol) in dry DMF (0.2 mL) was added and the flask was heated to 60 °C for 1 h. Me₃SiCl (0.41 μ L, 0.0031 mmol) was added and the mixture was stirred at 60 °C for 30 min.



Scheme 5 Completion of tangutorine (**1**).

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·2LiCl 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) and concentrated under reduced pressure. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording lactam **5** (28 mg, 52%) as a viscous oil. *R_f* 0.27 (EtOAc/heptane 1 : 1). FTIR (ATR) 2977, 1728, 1637, 1454, 1372, 1158 cm⁻¹. ¹H NMR (CDCl₃, 400 MHz): δ 8.13 (d, *J* = 7.0 Hz, 1H), 7.66 (d, *J* = 7.8 Hz, 1H), 7.41 (s, 1H), 7.35–7.22 (m, 2H), 6.15 (s, 1H), 5.71 (ddd, *J* = 17.3, 10.3, 7.2 Hz, 1H), 5.51 (s, 1H), 5.16–5.06 (m, 2H), 4.19 (q, *J* = 6.9 Hz, 2H), 4.21–4.12 (m, 1H), 3.19–3.13 (m, 1H), 3.09–2.93 (m, 3H), 2.54–2.44 (m, 2H), 2.40–2.16 (m, 3H), 2.07–1.96 (m, 1H), 1.88–1.68 (m, 4H), 1.66 (s, 9H), 1.28 (t, *J* = 7.2 Hz, 3H). ¹³C NMR (CDCl₃, 300 MHz): δ 169.5, 166.3, 149.2, 139.3, 138.5, 135.0, 130.0, 124.8, 123.9, 122.8, 122.0, 118.7, 117.3, 115.6, 114.8, 82.9, 61.1, 60.3, 45.5, 38.4, 31.3, 28.6, 27.9, 27.8, 22.6, 22.2, 13.7. HRMS (ESI) *m/z* calcd for C₂₉H₃₈N₂O₅ (M + Na)⁺: 517.2681, found: 517.2678.

6-Iodomethyl-1-(4-methoxybenzyl)-2-oxo-5-vinylpiperidine (6)

To a solution of compound **9** (105 mg, 0.38 mmol) in THF (4 mL), PPh₃ (120 mg, 0.46 mmol) and imidazole (39 mg, 0.57 mmol) were added. The reaction was heated to 70 °C and iodine (116 mg, 0.46 mmol) was added. After 30 min the reaction was cooled to room temperature and concentrated *in vacuo*. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording compound **6** (140 mg, 67%) as a viscous oil. *R_f* 0.82 (CH₂Cl₂/MeOH 9 : 1). FTIR (ATR) 2948, 1642, 1512, 1244, 519 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 vinylmagnesium 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 washed with aqueous Na₂S₂O₃ (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. *R_f* 0.41 (EtOAc/heptane 1 : 1). 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), 5.35 (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, 61.2, 54.8, 48.1, 38.6, 28.3, 22.9, 13.7. HRMS (ESI) *m/z* calcd for C₁₈H₂₃NO₄Na (M + Na)⁺: 340.1537, found: 340.1525.

6-Hydroxymethyl-1-(4-methoxybenzyl)-2-oxo-5-vinylpiperidine (9)

To a cooled solution (0 °C) of compound **8** (0.95 g, 3.0 mmol) in THF (30 mL) LiEt₃BH (9.0 mL, 9.0 mmol, 1 M solution in THF) was added. After 1.5 h of stirring at 0 °C another equivalent of LiEt₃BH (1.0 mL, 1.0 mmol) was added and the reaction was stirred for 2 h. The reaction was then quenched with ice-water and the product 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 CH₂Cl₂/MeOH 9 : 1) affording compound **9** (0.78 g, 95%) as a colorless oil. *R_f* 0.41 (CH₂Cl₂/MeOH 9 : 1). FTIR (ATR) 3376, 2948, 1613, 1512 cm⁻¹. ¹H NMR (CDCl₃, 400 MHz): δ 7.20 (d, *J* = 8.7 Hz, 2H), 6.85 (d, *J* = 8.7 Hz, 2H), 5.64–5.54 (m, 1H), 5.07–5.00 (m, 3H), 4.25 (d, *J* = 7.4 Hz, 1H), 3.79 (s, 3H), 3.79–3.73 (m, 1H), 3.64–3.56 (m, 1H), 3.21–3.16 (m, 1H), 2.72–2.63 (m, 1H), 2.58–2.37 (m, 2H), 2.05–1.95 (m, 2H), 1.72–1.60 (m, 1H). ¹³C NMR (CDCl₃, 75 MHz): δ 171.0, 158.5, 138.5, 129.2, 128.9, 116.0, 113.6, 61.1, 60.6, 54.8, 46.9, 38.3, 30.0, 23.8. HRMS (ESI) *m/z* calcd for C₁₆H₂₁NO₃Na (M + Na)⁺: 298.1421, found: 298.1419.

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. Me₃SiCl (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·2LiCl 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. *R_f* 0.25 (EtOAc/heptane 1 : 1). 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). ^{13}C NMR (CDCl_3 , 75 MHz): δ 169.7, 166.3, 158.4, 139.4, 138.4, 129.4, 128.9, 124.8, 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 $\text{C}_{22}\text{H}_{29}\text{NO}_4\text{Na}$ ($\text{M} + \text{Na}$) $^+$: 394.1997, found: 394.1994.

4-Vinylhex-5-enoic acid 4-methoxybenzylamide (11)

Compound **11** (31 mg, 46%) was isolated as a side product from the organozinc/copper coupling with compound **6**. R_f 0.43 (EtOAc/heptane 1 : 1). FTIR (ATR) 3282, 3073, 2930, 1641, 1512, 1246 cm^{-1} . ^1H NMR (CDCl_3 , 400 MHz): δ 7.20 (d, $J = 8.6$ Hz, 2H), 6.86 (d, $J = 8.7$ Hz, 2H), 5.75–5.64 (m, 2H), 5.62 (br s, 1H), 5.05–4.96 (m, 4H), 4.36 (d, $J = 5.6$ Hz, 2H), 3.80 (s, 3H), 2.71 (q, $J = 7.4$ Hz, 1H), 2.19 (t, $J = 7.4$ Hz, 2H), 1.79 (dt, $J = 7.8$, 7.4 Hz, 2H). ^{13}C NMR (CDCl_3 , 75 MHz): δ 171.9, 158.6, 139.9, 129.9, 128.8, 114.5, 113.6, 54.8, 46.9, 42.6, 33.8, 29.3. HRMS (ESI) m/z calcd for $\text{C}_{16}\text{H}_{21}\text{NO}_2\text{Na}$ ($\text{M} + \text{Na}$) $^+$: 282.1472, found: 282.1470.

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*. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1 to 2 : 1) affording compound **12** (34 mg, 86%) as a colorless oil. R_f 0.16 (EtOAc/heptane 1 : 1). FTIR (ATR) 2933, 1708, 1639, 1512, 1244 cm^{-1} . ^1H NMR (CDCl_3 , 400 MHz): δ 7.13 (d, $J = 8.8$ Hz, 2H), 6.84 (d, $J = 8.8$ Hz, 2H), 6.67 (d, $J = 1.3$ Hz, 1H), 5.06 (d, $J = 15.4$ Hz, 1H), 4.42 (d, $J = 15.4$ Hz, 1H), 4.17 (q, $J = 7.1$, 7.0 Hz, 2H), 3.79 (s, 3H), 3.08 (ddd, $J = 12.2$, 9.8, 2.5 Hz, 1H), 2.76–2.59 (m, 2H), 2.55–2.31 (m, 3H), 2.23–2.09 (m, 1H), 2.05–1.97 (m, 1H), 1.60 (m, 1H), 1.42 (m, 1H), 1.27 (t, $J = 7.1$ Hz, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ 170.5, 166.1, 158.1, 138.7, 129.3, 127.9, 126.7, 113.5, 60.1, 57.6, 54.8, 44.5, 39.5, 32.4, 26.4, 25.9, 24.0, 13.7. HRMS (ESI) m/z calcd for $\text{C}_{20}\text{H}_{25}\text{NO}_4\text{Na}$ ($\text{M} + \text{Na}$) $^+$: 366.1684, found: 366.1681.

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_2Cl_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_2Cl_2 (2 \times 40 mL), dried over Na_2SO_4 and concentrated *in vacuo*. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording compound **15** (516 mg, 85%). R_f 0.14 (EtOAc/heptane 1 : 1). ^1H NMR (CDCl_3 , 400 MHz): δ 7.58 (s, 1H), 6.29–6.26 (m, 1H), 4.29 (q, $J = 7.1$ Hz, 2H), 2.53–2.50 (m, 4H), 1.33 (t, $J = 7.1$ Hz, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ 169.2, 161.2, 128.4, 113.5, 61.4, 28.7, 20.3, 13.7.

3-[2-(6-Ethoxycarbonyl-2-oxo-3,4-dihydro-2H-pyridin-1-yl)ethyl]indole-1-carboxylic acid *tert*-butyl ester (16)

Lactam **15** (121 mg, 0.72 mmol) was dissolved in DMF (8 mL) and Boc-protected 3-(2-bromoethyl)indole (**14**, 347 mg, 1.07 mmol) was added. NaH (45 mg, 0.9 mmol) was gradually added to the mixture over 2.5 h. The reaction was then stirred overnight at room temperature, diluted with EtOAc/heptane 1 : 1 (10 mL), cooled to 0 °C and quenched with H_2O (10 mL). The organic layer was extracted with EtOAc (3 \times 10 mL), dried (MgSO_4) and concentrated under reduced pressure. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording compound **16** (155 mg, 53%) as a viscous oil. R_f 0.40 (EtOAc/heptane 1 : 1). FTIR (ATR) 2977, 1724, 1678, 1367, 1255, 1157 cm^{-1} . ^1H NMR (CDCl_3 , 400 MHz): δ 8.11 (d, $J = 6.1$ Hz, 1H), 7.62 (d, $J = 7.7$ Hz, 1H), 7.36 (s, 1H), 7.32–7.20 (m, 2H), 6.27 (t, $J = 5.0$ Hz, 1H), 4.11 (dq, $J = 7.1$, 0.5 Hz, 2H), 4.10–4.04 (m, 2H), 3.01–2.95 (m, 2H), 2.50 (t, $J = 7.6$ Hz, 2H), 2.35–2.26 (m, 2H), 1.66 (s, 9H), 1.25 (dt, $J = 7.1$, 0.5 Hz, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ 170.1, 162.1, 149.2, 135.1, 134.5, 130.0, 123.8, 122.8, 121.9, 119.9, 118.7, 117.2, 114.7, 82.9, 60.9, 42.9, 30.4, 27.8, 23.9, 19.4, 13.6. HRMS (ESI) m/z calcd for $\text{C}_{23}\text{H}_{28}\text{N}_2\text{O}_5\text{Na}$ ($\text{M} + \text{Na}$) $^+$: 435.1898, found: 435.1896.

3-[2-(2-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_2O (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_2O (1 mL) was added and the temperature was slowly warmed to –10 °C. The reaction was diluted with Et_2O , quenched with 0.1 M HCl (10 mL), washed with aqueous $\text{Na}_2\text{S}_2\text{O}_3$ (2 \times 10 mL), NaHCO_3 (10 mL) and H_2O (10 mL), dried over MgSO_4 and concentrated *in vacuo*. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 1) affording compound **17** (0.95 g, 72%) as a viscous oil. R_f 0.26 (EtOAc/heptane 1 : 1). FTIR (ATR) 2977, 1731, 1650, 1454, 1373, 1158 cm^{-1} . ^1H NMR (CDCl_3 , 400 MHz): δ 8.12 (d, $J = 7.8$ Hz, 1H), 7.63 (d, $J = 7.7$ Hz, 1H), 7.39 (s, 1H), 7.28 (m, 2H), 5.71 (ddd, $J = 17.3$, 10.4, 7.0 Hz, 1H), 5.19–5.10 (m, 2H), 4.22 (dq, $J = 7.1$, 0.6 Hz, 2H), 4.18–4.12 (m, 1H), 3.91 (d, $J = 4.1$ Hz, 1H), 3.10–2.86 (m, 3H), 2.85–2.77 (m, 1H), 2.56–2.38 (m, 2H), 1.98–1.87 (m, 1H), 1.78–1.69 (m, 1H), 1.66 (s, 9H), 1.27 (dt, $J = 7.1$, 0.7 Hz, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ 171.0, 169.4, 149.2, 136.4, 135.0, 129.9, 123.9, 122.8, 122.1, 118.6, 117.1, 116.4, 114.8, 83.0, 65.0, 61.3, 47.3, 39.2, 28.5, 27.8, 23.2, 22.4, 13.8. HRMS (ESI) m/z calcd for $\text{C}_{25}\text{H}_{32}\text{N}_2\text{O}_5\text{Na}$ ($\text{M} + \text{Na}$) $^+$: 463.2211, found: 463.2209.

3-Vinyl-1,2,3,4,6,7,12,12b-octahydroindolo[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_2Cl_2 (10 mL) and quenched with aqueous NaHCO_3 ,

(10 mL). The organic layer was washed with H₂O (2 × 10 mL), dried over MgSO₄ and concentrated *in vacuo*. The residue was purified by flash column chromatography (EtOAc/heptane 1 : 2) affording compound **19** (13.0 mg, 68%) as a colorless oil. *R*_f 0.48 (EtOAc/heptane 1 : 1). FTIR (ATR) 3342, 2916, 1717, 1455, 611 cm⁻¹. ¹H NMR (CDCl₃, 400 MHz): δ 7.69 (br s, 1H), 7.46 (d, *J* = 7.8 Hz, 1H), 7.30 (d, *J* = 7.7 Hz, 1H), 7.11 (ddt, *J* = 15.9, 7.1, 1.2 Hz, 2H), 5.68 (m, 1H), 5.04 (dd, *J* = 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). ¹³C NMR (CDCl₃, 75 MHz): δ 167.7, 137.9, 135.5, 133.5, 121.0, 119.0, 117.7, 116.1, 110.2, 108.0, 105.7, 72.6, 60.3, 58.8, 50.7, 44.6, 29.7, 28.3, 21.4, 13.9. HRMS (ESI) *m/z* calcd for C₂₀H₂₅N₂O₂ (M + H)⁺: 325.1918, found: 325.1916.

3-[2-(2-Hydroxymethyl-6-oxo-3-vinylpiperidin-1-yl)ethyl]indole-1-carboxylic acid *tert*-butyl ester (**20**)

To a cooled solution (0 °C) of compound **17** (93 mg, 0.21 mmol) in THF (2.5 mL) LiEt₃BH (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 × 40 mL), dried over MgSO₄ and concentrated *in vacuo*. The residue was purified by flash chromatography (EtOAc/heptane 1 : 1 to CH₂Cl₂/MeOH 9 : 1) affording compound **20** (74 mg, 88%) as a viscous oil. *R*_f 0.35 (CH₂Cl₂/MeOH 9 : 1). FTIR (ATR) 3322, 1731, 1615, 1455, 1370 cm⁻¹. ¹H NMR (CDCl₃, 400 MHz): δ 8.11 (d, *J* = 6.7 Hz, 1H), 7.69–7.60 (m, 1H), 7.39 (d, *J* = 3.3 Hz, 1H), 7.33–7.19 (m, 2H), 5.73–5.55 (m, 1H), 5.16–5.00 (m, 2H), 4.11–4.00 (m, 1H), 4.00–3.64 (m, 2H), 3.32–3.14 (m, 2H), 3.08–2.85 (m, 2H), 2.53–2.40 (m, 2H), 2.39–2.23 (m, 1H), 2.07–1.84 (m, 1H), 1.68–1.57 (m, 10H). ¹³C NMR (CDCl₃, 75 MHz): δ 170.7, 170.4, 149.2, 138.5, 138.3, 135.0, 130.0, 130.0, 124.0, 123.9, 122.7, 122.1, 118.8, 118.6, 117.4, 117.3, 115.8, 115.7, 115.5, 114.8, 83.0, 82.9, 62.9, 62.0, 62.0, 61.9, 61.6, 46.0, 45.9, 45.8, 37.8, 37.7, 37.4, 29.4, 29.2, 29.0, 27.8, 23.1, 22.8, 22.7, 22.6. HRMS (ESI) *m/z* calcd for C₂₃H₃₀N₂O₄Na (M + Na)⁺: 421.2106, found: 421.2103.

3-[2-(2-Iodomethyl-6-oxo-3-vinyl-piperidin-1-yl)ethyl]-indole-1-carboxylic acid *tert*-butyl ester (**21**)

Compound **20** (20 mg, 0.125 mmol) was dissolved in THF (2 mL) and PPh₃ (50 mg, 0.19 mmol), imidazole (13 mg, 0.19 mmol) and iodine (48 mg, 0.19 mmol) were added and stirred at room temperature for 4 h. The reaction was diluted with CH₂Cl₂, washed with Na₂S₂O₃ (20 mL) and H₂O (20 mL), dried over Na₂SO₄ and concentrated *in vacuo*. The residue was purified by flash column chromatography (heptane → EtOAc/heptane 1 : 3 to 1 : 2) affording compound **21** (50 mg, 78%). *R*_f 0.80 (CH₂Cl₂/MeOH 9 : 1). FTIR (ATR) 1975, 1731, 1646, 1455, 1373, 1157 cm⁻¹. ¹H NMR (CDCl₃, 400 MHz): δ 8.13 (d, *J* = 7.0 Hz, 1H), 7.66 (d, *J* = 7.7 Hz, 1H), 7.35–7.23 (m, 3H), 5.67–5.56 (m, 1H), 5.23–5.10 (m, 2H), 4.20–2.11 (m, 1H), 3.43–3.37 (m, 1H), 3.36–3.29 (m, 1H), 3.16–2.91 (m, 4H), 2.72–2.64 (m, 1H), 2.55–2.36 (m, 2H), 1.95–1.85 (m, 1H), 1.75–1.63 (m, 10H). ¹³C NMR (CDCl₃, 75 MHz): δ 169.8, 149.2, 137.8, 135.0, 129.9, 124.0, 122.7, 122.1, 118.6, 117.2, 116.8, 114.8, 83.0, 60.9, 44.9, 40.9, 29.7, 27.8, 22.9,

22.6, 9.3. HRMS (ESI) *m/z* calcd for C₂₃H₂₉IN₂O₃Na (M + Na)⁺: 531.1123, found: 531.1121.

2,4a,5,6,11b,12,13,13a-Octahydro-1*H*-4b,11-diazaindeno[2,1-*a*]phenanthrene-3,11-dicarboxylic acid 11-*tert*-butyl 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. *R*_f 0.63 (EtOAc/heptane 2 : 1). FTIR (ATR) 2933, 1725, 1477, 732 cm⁻¹. ¹H NMR (CDCl₃, 400 MHz): δ 8.16 (d, *J* = 8.0 Hz, 1H), 7.41 (d, *J* = 7.2 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, 3H), 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, 141.8, 136.4, 136.0, 129.4, 128.8, 123.4, 122.1, 117.4, 115.3, 114.5, 83.1, 63.3, 60.0, 58.2, 36.3, 33.3, 30.8, 27.8, 26.8, 25.8, 25.3, 21.7, 13.8. HRMS (ESI) *m/z* calcd for C₂₇H₃₄N₂O₄ [M + H]⁺: 451.2599, found: 451.2597.

1,2,4a,5,6,11,11b,12,13,13a-Decahydro-4b,11-diazaindeno[2,1-*a*]phenanthrene-3-carboxylic acid ethyl ester (**23**)

Compound **23** (4 mg, 20%) was isolated as a side product of the Bischler–Napieralski reaction with compound **4**. *R*_f 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, 1H), 7.21 (d, *J* = 7.9 Hz, 1H), 7.16–7.06 (m, 2H), 6.68 (s, 1H), 4.21 (q, *J* = 7.2, 7.1 Hz, 2H), 3.62 (ddd, *J* = 10.4, 4.8, 2.1 Hz, 1H), 3.48 (d, *J* = 11.4 Hz, 1H), 2.98–2.88 (m, 1H), 2.79 (d, *J* = 15.5 Hz, 1H), 2.62 (dd, *J* = 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, *J* = 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, 60.4, 45.7, 40.7, 30.3, 30.0, 26.0, 25.0, 22.1, 14.3. HRMS (ESI) *m/z* calcd for C₂₂H₂₆N₂O₂ [M + H]⁺: 351.2074, found: 351.2073.

Deprotection of 2,4a,5,6,11b,12,13,13a-octahydro-1*H*-4b,11-diazaindeno[2,1-*a*]phenanthrene-3,11-dicarboxylic acid 11-*tert*-butyl 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%). *R*_f 0.21 (EtOAc/heptane 1 : 1).

Notes and references

- 1 W. A. Creasey in *The Monoterpenoid Indole Alkaloids*, A. J. E. Saxton (Ed.); Wiley, Chichester, 1983, vol. 4, 783.
- 2 G. Blaskó, H. Knight, K. Honty and C. Szántey, *Liebigs Ann. Chem.*, 1986, 655–663.
- 3 G. Stork, P. C. Tang, M. Casey, B. Goodman and M. Toyota, *J. Am. Chem. Soc.*, 2005, **127**, 16255–16262.
- 4 J.-A. Duan, I. D. Williams, C.-T. Che, R.-H. Zhou and S.-X. Zhao, *Tetrahedron Lett.*, 1999, **40**, 2593–2596.
- 5 B. P. L. Liu, E. Y. Y. Chong, F. W. K. Cheung, J.-A. Duan, C.-T. Che and W. K. Liu, *Biochem. Pharmacol.*, 2005, **70**, 287–299.
- 6 T. Putkonen, A. Tolvanen and R. Jokela, *Tetrahedron Lett.*, 2001, **42**, 6593–6594.
- 7 T. Putkonen, A. Tolvanen, R. Jokela, S. Caccamese and N. Parrinello, *Tetrahedron*, 2003, **59**, 8589–8595.
- 8 S. Luo, C. A. Zifcsak and R. P. Hsung, *Org. Lett.*, 2003, **5**, 4709–4712.
- 9 T.-L. Ho and C.-K. Chen, *Helv. Chim. Acta*, 2006, **89**, 122–126.
- 10 R. Salame, E. Gravel, K. Leblanc and E. Poupon, *Org. Lett.*, 2009, **11**, 1891–1994.
- 11 T. Nemoto, E. Yamamoto, R. Franzen, T. Fukuyama, R. Wu, T. Fukamachi, H. Kobayashi and Y. Hamada, *Org. Lett.*, 2010, **12**, 872–875.
- 12 S. S. Kinderman, J. H. van Maarseveen, H. E. Schoemaker, H. Hiemstra and F. P. J. T. Rutjes, *Org. Lett.*, 2001, **3**, 2045–2047.
- 13 For an excellent overview of formation of cyclic compounds using RCM, see: *Metathesis in Natural Product Synthesis*, J. Cossy, S. Arseniyadis and C. Meyer, (ed.); Wiley-VCH, Weinheim, 2010.
- 14 M. Arisawa, H. Terada, M. Nakagawa and A. Nishida, *Angew. Chem., Int. Ed.*, 2002, **41**, 4732–4735.
- 15 K. F. W. Hekking, L. Lefort, A. H. M. de Vries, F. L. van Delft, H. E. Schoemaker, J. G. de Vries and F. P. J. T. Rutjes, *Adv. Synth. Catal.*, 2008, **350**, 95–106.
- 16 S. A. M. W. van den Broek, P. G. W. Rensen, F. L. van Delft and F. P. J. T. Rutjes, *Eur. J. Org. Chem.*, 2010, 5906–5912.
- 17 N. Toyooka, Z. Dejun, H. Nemoto, H. M. Garraffo, T. F. Spande and J. W. Daly, *Tetrahedron Lett.*, 2006, **47**, 581–582.
- 18 P. Knochel and R. D. Singer, *Chem. Rev.*, 1993, **93**, 2117–2188.
- 19 J. Leonard, D. Appleton and S. P. Fearnley, *Tetrahedron Lett.*, 1994, **35**, 1071–1074.
- 20 (a) G. Fodor, J. Gal and B. A. Philips, *Angew. Chem., Int. Ed. Engl.*, 1972, **11**, 6593–6594; (b) E. D. Cox and J. M. Cook, *Chem. Rev.*, 1995, **95**, 1797–1842.