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Symmetric cytotoxic trimeric and dimeric indole alkaloids isolated from *Bousigonia angustifolia*†Bao-Bao Shi,^{a,b} Jing-Song Lu,^c Jing Wu,^{a,b} Mei-Fen Bao^{a,b} and Xiang-Hai Cai^{id} *^a

A symmetric monoterpenoid indole alkaloid trimer, bousangustine A, is reported for the first time, as well as the dimeric alkaloids bousangustines B and C; these were isolated from the trunks of *Bousigonia angustifolia*. The structures, which feature a symmetric 6/9/5/6 ring system, were elucidated using comprehensive spectroscopic analysis. Their absolute configurations were determined via X-ray crystal diffraction, as well as computational chemistry. They can be constructed through Friedel–Crafts and free radical reactions, respectively. These compounds exhibited significant cytotoxicity against tumor cells.

Introduction

Since the development of bisindole vinblastine (VBL) and vincristine (VCR) into drugs, dimeric monoterpenoid indole alkaloids (MIAs) have attracted extensive attention. Owing to the inactive units of velbenamine and vindoline in VBL and VCR, the polymerization of indoles appears to be a crucial approach to obtain structural complexity, as well as bioactive diversity.¹ There are two forms of polymerization of MIAs (Fig. S1B in ESI†). One is through a direct connection, such as asymmetric voacandimine A,² coryzeylamine,³ deformylcoryzeylamine,³ suadimins A–C,⁴ and symmetric geleganidine B.⁵ The other is through an indirect connection, such as symmetric pleiokomenines A,⁶ meloyines III,⁷ melofusine I,⁸ melomorsine I,⁸ and voacinol² using methylene, as well as geleganidine C through a carbonyl.⁵ Additionally, trimeric MIAs are unusual, for example, psychotropine from *Psychotria pilifera*,⁹ ervadivamines A/B from *Ervatamia divaricata*,¹⁰ and 3-hydroxy-14'-(3 α '-tabersonyl)voafrine B and 14-(3 α '-tabersonyl)-voafrine B in *Catharanthus roseus*,¹¹ bousigonine B in *Bousigonia mekongensis* have been previously reported.¹² These trimers are assembled by a single bond in sequence and are asymmetric structures. As part of our recent studies on dimeric^{7,8,13,14} and trimeric alkaloids,¹⁵ we have phytochemically researched plants of the genus *Bousigonia*, which contain bisindoles and

dimers.¹⁶ This paper describes the isolation, structural determination, and potential bioactivity of three newly isolated MIAs (1–3) together with three known MIAs (4–6) (Fig. 1) obtained from the trunks of *B. angustifolia* Pierre.

Results and discussion

Compounds 1–3 were obtained as an amorphous powder and exhibited a positive reaction to Dragendorff's reagent. The ¹H NMR spectrum of 1 revealed signals for four coupled indole protons (δ_{H} 7.10, 7.26, 7.18, 7.26), one olefinic proton (δ_{H} 5.06), one methyl (δ_{H} 0.60), one methine (δ_{H} 5.20, s), and six methylene protons (δ_{H} 1.39, 1.40, 1.80, 1.81, 2.07, 2.33, 2.34, each 1H, m; δ_{H} 1.38, 1H, d; δ_{H} 3.29 and 3.87, each 1H, dd; δ_{H} 1.67, 1H, td; and δ_{H} 1.13, 1H, dq) (Table 1). The 20 carbon signals in the ¹³C NMR and DEPT spectra of 1 could be classified as seven quaternary carbons (including one carbonyl at δ_{C} 179.9 and five olefinic ones at δ_{C} 118.1, 131.1, 131.3, 139.5 and 141.6), six methines (including five olefinic ones at δ_{C} 111.1, 127.2, 127.9, 128.9 and 132.5), six methylenes (δ_{C} 20.3, 29.2, 31.1, 33.7, 37.9 and 44.4) and one methyl at δ_{C} 8.5 (Table 1). The molecular formula C₅₈H₆₄N₆O₃ was established using the ¹³C NMR and high-resolution electron ionization mass spectrometry (HREIMS) data (m/z 915.4937 [M + Na]⁺, calculated for C₅₈H₆₄N₆O₃Na, 915.4932), which indicated 30 indices of hydrogen deficiency. However, the above described NMR data for 1 showed 20 carbon and 22 proton signals, only accounting for around one-third of the signals compared with the molecular formula. Therefore, compound 1 has a highly symmetrical structure. The planar structure was further elucidated by 2D NMR experiments. Analysis of the ¹H–¹H correlation spectroscopy (COSY) and heteronuclear multiple quantum coherence (HMQC) spectra revealed the presence of three molecular fragments: fragment A (C₃–C₁₄–C₁₅), fragment B (C₁₆–C₁₇),

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Fig. 1 Chemical structures of bousangustines A–C (1–3) and the known compounds 4–6.

Table 1 ^1H and ^{13}C NMR spectroscopic data for 1–3 in methanol- d_4 (δ in ppm and J in Hz)

No.	δ_{C} (1) ^b	δ_{H} (1) ^a	δ_{C} (2) ^b	δ_{H} (2) ^a	δ_{C} (3) ^c	δ_{H} (3) ^a
2/2'/2''	179.9 s		180.1 s		177.4 s	
3/3'/3''	44.4 t	3.87 dd (12.4, 4.6) 3.29 dd (12.4, 4.0)	44.4 t	3.99 dd (12.2, 4.6) 3.50 td (12.2, 4.9)	37.4 t	4.19 d (13.7) 3.02 m
5/5'/5''	131.1 s		129.2 s		165.8 s	
6/6'/6''	111.1 d	5.06 s	110.1 d	5.38 s	129.9 s	
7/7'/7''	118.1 s		118.2 s		154.5 s	
8/8'/8''	141.6 s		141.6 s		133.6 s	
9/9'/9''	132.5 d	7.26 dd (7.7, 1.4)	132.4 d	7.36 dd (7.6, 1.7)	130.3 d	6.80 d (7.3)
10/10'/10''	127.9 d	7.18 td (7.7, 1.5)	128.1 d	7.28 td (7.6, 1.5)	128.8 d	6.80 t (7.3)
11/11'/11''	128.9 d	7.26 td (7.7, 1.4)	128.9 d	7.34 td (7.6, 1.7)	130.4 d	7.19 t (7.3)
12/12'/12''	127.2 d	7.10 dd (7.7, 1.5)	127.4 d	7.18 dd (7.6, 1.5)	127.1 d	7.00 d (7.3)
13/13'/13''	139.5 s		139.6 s		135.3 s	
14/14'/14''	20.3 t	2.07 m 1.81 m	20.3 t	2.15 m 1.90 m	21.1 t	1.55 m
15/15'/15''	33.7 t	1.67 td (13.5, 3.1) 1.39 m	33.7 t	1.72 td (13.5, 3.1) 1.46 m	34.5 t	1.79 m 1.67 d (14.1)
16/16'/16''	29.2 t	2.34 m 1.80 m	29.2 t	2.40 m 1.86 t (7.8)	28.2 t	1.96 m
17/17'/17''	37.9 t	2.33 m 1.40 m	38.1 t	2.40 m 1.46 m	26.6 t	1.79 m 1.52 t (4.6)
18/18'/18''	8.5 q	0.60 t (7.4)	8.5 q	0.69 t (7.3)	7.5 q	0.48 t (7.7)
19/19'/19''	31.1 t	1.13 dq (14.6, 7.4) 1.38 dq (14.6, 7.4)	31.2 t	1.19 dq (14.6, 7.3) 1.46 dq (14.6, 7.3)	25.9 t	1.04 dq (15.2, 7.7) 1.45 dq (15.2, 7.7)
20/20'/20''	40.3 s		40.2 s		45.5 s	
21/21'/21''	131.3 s		130.7 s		93.8 s	
22	35.1 d	5.20 s	25.0 t	3.74 s		

^a Recorded at: 400 MHz. ^b Recorded at: 125 MHz. ^c Recorded at: 150 MHz.

fragment C (C₁₈–C₁₉) and an indole ring (Fig. 2). The hetero-nuclear multiple bond correlation (HMBC) correlations from H-3 to C-5 (δ_{C} 131.1) and C-21, from H-6 to C-7 (δ_{C} 118.1), C-8 (δ_{C} 141.6) and C-21, and from H-9 to C-7 indicated the presence of a pyrrole ring. Further analysis of the NMR spectrum suggested that **1** was closely related to known compounds **4** and **5**.¹⁷ A careful comparison of the NMR data for **1** and **4** (Fig. S26 and S27†) disclosed the presence of an aldehyde group in **4**, and a methine (δ_{C} 35.1 and δ_{H} 5.20) appeared in **1**. The HMBC correlations from H-15 to C-17 (δ_{C} 37.9), C-19 (δ_{C} 31.1) and C-21 (δ_{C} 131.3), from H-19 to C-15 (δ_{C} 33.7), C-17 and C-21, and from H-17 to C-15, C-19 and C-21 further supported this similarity between **1** and **4**. The methine was connected with C-5 by the key HMBC correlations from its proton signal

δ_{H} 5.20 to C-5 and C-6 (δ_{C} 111.1), and from H-6 (δ_{H} 5.06) to C-5, C-8, C-21 and its carbon signal (δ_{C} 35.1). Furthermore, taking the molecular formula into consideration, this methine should connect to another two of the same units. Thus, the complete planar structure of **1** was established.

The molecular formula C₃₉H₄₄N₄O₂ with 20 degrees of unsaturation for alkaloid **2** was established by using the positive high resolution electrospray ionisation mass spectrometry (HRESIMS) ion at m/z 623.3355 ([M + Na]⁺, calculated, 623.3356). The ^{13}C NMR signals were only observed for 20 carbon atoms, indicating that **2** also has a symmetrical structure. The ^1H and ^{13}C NMR data of **2** were almost identical to those of compound **1** except for the methine group (CH-22) in **1**, there is a methylene group (δ_{C} 25.0) in **2** instead. This pre-

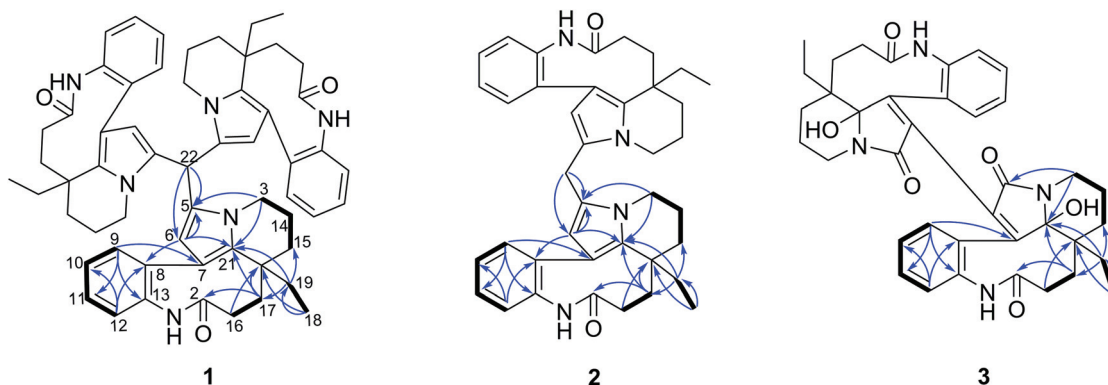


Fig. 2 Key HMBC and COSY correlations for compounds 1–3.

sumption was supported by the HMBC correlations from H-22 (δ_{H} 3.74, 2H) to C-5 (δ_{C} 129.2) and C-6 (δ_{C} 110.1), and from H-6 to C-5, C-21 (δ_{C} 130.7) and C-22 (δ_{C} 25.0). However, 2 had the molecular formula $\text{C}_{39}\text{H}_{44}\text{N}_4\text{O}_2$ according to the results from the HRESIMS, $\text{C}_{19}\text{H}_{20}\text{N}_2\text{O}$ less than compound 1. This difference suggests that 2 is a symmetric dimer of 4 through a methylene bridge. Therefore, the planar structure of 2 was completely established.

The molecular formula $\text{C}_{38}\text{H}_{42}\text{N}_4\text{O}_6$ with 20 degrees of unsaturation of alkaloid 3 was established by the positive HRESIMS ion at m/z 673.2992 ($[\text{M} + \text{Na}]^+$, calculated.

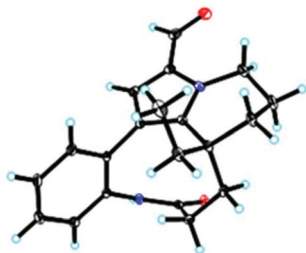


Fig. 3 The X-ray structure of compound 4.

673.2997). The NMR data (Table 1) showed signals for 19 carbons and 21 protons, only accounting for half the number expected from the molecular formula. This indicated that 3 should be a symmetric dimer. The ^1H NMR spectrum also revealed the same indole A ring (δ_{H} 6.80, 7.00, 6.80, 7.19), one methyl (δ_{H} 0.48, 3H), and six methylene protons. The 19 carbon signals shown in the ^{13}C NMR and DEPT spectra of 3 could be classified as eight quaternary carbons (including two carbonyls at δ_{C} 165.8 and 177.4; four olefinic ones at δ_{C} 129.9, 133.6, 135.3 and 154.5, and one heteroatom-bearing at δ_{C} 93.8), four indole methines (δ_{C} 127.1, 128.8, 130.3 and 130.4), six methylenes (δ_{C} 21.1, 25.9, 26.6, 28.2, 34.5 and 37.4), and one methyl (δ_{C} 7.5 q). The above described data for 1 was similar to that obtained for the known leuconolam (6),¹⁸ except for the absence of the olefinic methine signal at δ_{C} 128.1 and the presence of a quaternary carbon signal at δ_{C} 129.9 in 1. For compound 3, the absence of a signal for H-6 (δ_{H} 5.79 in 6), together with the continuous correlations of H-9 (δ_{H} 6.80)/H-10 (δ_{H} 6.80)/H-11 (δ_{H} 7.19)/H-12 (δ_{H} 7.00) in the COSY spectrum (Fig. 2), indicated that both units must be directly connected through C-6/C-6'.

Unfortunately, attempts to prepare single crystals of 1–3 were not successful. However, a single crystal of alkaloid 4,

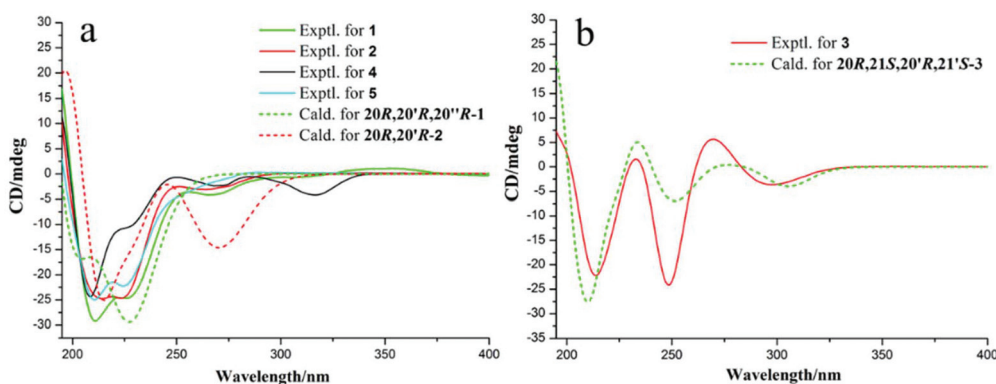


Fig. 4 (a) Experimental ECD spectra and calculated ECD spectra for 1–2 and 4–5; and (b) experimental ECD spectra and calculated ECD spectra of 3 at the M06-2X/Def2SVP level in methanol.

compounds were predicted to be identical. Therefore, the absolute configurations of **1** and **2** were determined to be 20*R*,20'*R*,20''*R* and 20*R*,20'*R*, respectively. Furthermore, the calculated electronic circular dichroism (ECD) spectra were used to support this prediction. Although the Cotton effects of **1** and **2** were stronger and slightly shifted compared to those observed for **4** and **5** (Fig. 4a), the tendencies of the CD curves of the four compounds in the range of 200 to 350 nm were relatively consistent, supporting their identical configurations. In addition, the identity of the measured CD and calculated ECD spectrum of **1** and **2** (Fig. 4a) further confirmed this conclusion. Similar to **1** and **2**, **4** and **5**, **3** and **6** were predicted to have the same absolute configurations. A further search of the previously published literature revealed leuconolam as an authentic sample of a natural product, and its structure was unambiguously determined using X-ray analysis.¹⁸ Further comparison of the experimental chemical shifts and the calculated and experimental ECD spectra of **6** (Table S5 and Fig. S43†) revealed that **6** was leuconolam. Therefore, the stereoconfiguration of **3** was temporarily deduced as 20*R*,21*S*,20''*R*,21'*S*. This assumption was confirmed by comparative analysis of the calculated and experimental ECD spectra. The identity of the measured circular dichroism (CD) and the calculated ECD spectra of **3** (Fig. 4b) supported this prediction. It should be mentioned that compound **3** possessed fast axial rotation rates in the order of seconds or faster and exhibited no axial chirality based on the correlation of the calculated energy barriers and rotation rates ($\Delta E_{\text{rot}} < 20 \text{ kcal mol}^{-1}$) (Fig. S42†).¹⁹

All of the isolates were evaluated *in vitro* against SMMC-7721, HeLa, HepG2, and A549 tumor cell lines.

No.	SMMC-7721	HeLa	HepG2	A549
1	10.99 ± 0.34	12.50 ± 1.11	16.3 ± 0.15	16.93 ± 0.33
2	4.31 ± 0.06	4.40 ± 0.30	7.02 ± 0.55	16.21 ± 0.01
3	>40	>40	>40	>40
4	0.52 ± 0.04	0.60 ± 0.03	0.76 ± 0.05	>40
5	1.89 ± 0.22	1.76 ± 0.02	3.46 ± 0.22	>40
6	>40	>40	>40	>40
Vinorelbine	3.02 ± 0.21	0.60 ± 0.03	0.76 ± 0.05	2.23 ± 0.06



Compound **4** exhibited significant cytotoxicity against the SMMC-7721, HeLa and HepG2 cell lines with IC_{50} values of 0.52 ± 0.04 , 0.60 ± 0.03 and 0.76 ± 0.05 μ M, respectively. Compounds **1** and **2** showed moderate cytotoxic activities against SMMC-7721, HeLa, HepG2, and A549 cells, with IC_{50} values ranging from 4.31 to 16.93 μ M. Compounds **3** and **6** showed no cytotoxicity at 40 μ M (Table 2).

Bousangustines A–C (**1**–**3**) are novel symmetrical MIAs trimer and dimers. Together with these, three known MIAs, rhazinal (**4**), rhazinilam (**5**), and leuconolam (**6**), were simultaneously isolated. Hence, we propose a plausible biosynthetic pathway for alkaloids **1**–**3** (Scheme 1). The pathway for **1**–**2** could start from **4** and **5** through a Friedel–Crafts reaction under acid conditions, generating the hydroxy intermediate I. I is then dehydrated to produce intermediate II. II is further coupled with **5**, forming trimer **1** (Scheme 1, route A). On the other hand, II is reduced and gives dimer **2** (route B). Unlike the formation of **1** and **2**, **6** is oxidized to generate the free radical intermediate III. The coupling of both units III gives **3** after isomerization (route C).

Conclusions

In summary, three previously unreported bousangustines A–C were isolated from *B. angustifolia*. Bousangustine A is the first reported symmetric MIA trimer and bousangustines B–C are symmetric dimeric MIAs. Their absolute configurations were determined using X-ray crystal diffraction and ECD calculations. Bousangustines A and B may be constructed through a Friedel–Crafts reaction, while bousangustine C could be formed through free radical coupling from simultaneously isolated monomers. The liquid chromatography mass spectrometry (LC-MS) detection results of these novel isolates disclosed their natural properties. Furthermore, these macrocyclic compounds exhibited excellent cytotoxic activities. These findings enrich our knowledge of the chemical diversity of MIAs and will attract the interest of both chemical synthetic and pharmaceutical chemists.

Experimental section

General experimental procedures

The optical rotations were measured using a Jasco P-1020 digital polarimeter (Jasco International Co., Tokyo, Japan). UV spectra were recorded on a Shimadzu 2401PC spectrophotometer (Shimadzu Corp., Kyoto, Japan). CD spectra were obtained on a Chirascan V100 circular dichroism spectrometer (Applied Photophysics, Surrey, UK). The MS data were recorded on an UPLC-IT-TOF MS (Shimadzu Corp., Kyoto, Japan) or Agilent G6230 TOF MS (Applied Biosystems, Ltd, Warrington, UK). 1H , ^{13}C and 2D NMR spectra were obtained on Bruker AVANCE III-600, AVANCE III-500 and AVANCE III-400 MHz spectrometers (Bruker BioSpin GmbH, Rheinstetten, Germany) with $SiMe_4$ as an internal standard. The chemical shifts (δ) are

expressed in ppm with reference to the solvent signals. X-ray crystallographic analysis using Cu K α radiation was performed on a Bruker D8 QUEST instrument (Bruker, Karlsruhe, Germany). Column chromatography (CC) was performed on either silica gel (200–300 mesh, Qingdao Marine Chemical Co., Ltd, Qingdao, China) or RP-18 silica gel (20–45 μ m, Fuji Silysia Chemical Ltd, Japan). Fractions were monitored by TLC on silica gel plates (GF254, Qingdao Marine Chemical Co., Ltd, Qingdao, China), and spots were visualized with Dragendorff's reagent spray. Medium pressure liquid chromatography (MPLC) was performed using a Buchi pump system coupled with RP-18 silica gel-packed glass columns (15 \times 230 and 26 \times 460 mm, respectively). High performance liquid chromatography (HPLC) was performed using Waters 1525E pumps (Waters Corp., Milford, MA, USA) coupled with analytical semi-preparative or preparative XBridge C_{18} columns (4.6 \times 150, 10 \times 150, and 19 \times 250 mm, respectively). The HPLC system employed a Waters 2998 photodiode array detector and a Waters fraction collector III (Waters Corp., Milford, MA, USA).

Plant material

Trunks of *Bousigonia angustifolia* Pierre were collected in Dec 2018 in areas along the Mengla County, Yunnan Province, P. R. China, and identified by Dr Jie Cai. A voucher specimen (No. Cai20181228) was deposited in the State Key Laboratory of Phytochemistry and Plant Resources in West China, Kunming Institute of Botany, Chinese Academy of Sciences.

Extraction and separation

The dried and powdered trunks of *B. angustifolia* (25 kg) were extracted with MeOH (60 L \times 3) at room temperature, these were then filtered and the solvent was evaporated *in vacuo*. The extract was dissolved in 0.5% aqueous HCl solution and extracted with ethyl acetate (EtOAc) three times. The remaining acidic aqueous solution was basified with 10% NH_4OH to pH 7–8, and subsequently extracted with EtOAc. This afforded 210 g of the crude alkaloidal fraction. This EtOAc extract (210 g) was subjected to column chromatography (CC) over silica gel and eluted with gradient $CHCl_3$ –MeOH (1 : 0–0 : 1, v/v) to afford ten fractions (I–X). Fraction I (17.4 g) was chromatographed on a C_{18} MPLC column eluted with a gradient of MeOH– H_2O (10 : 90–100 : 0, v/v) to give the eighteen subfractions I-1–I-18. Fraction I-12 (2.2g) was separated using a Sephadex LH-20 column eluted with MeOH. Six subfractions (I-12-1–I-12-6) were collected. I-12-6 (0.4 g) was separated using a C_{18} MPLC column with a gradient of MeOH– H_2O (60 : 40–90 : 10, v/v) to afford three subfractions (I-12-6-1–I-12-6-3). Fraction I-12-6-1 (0.11 g) was purified using a preparative C_{18} HPLC column with a gradient of MeCN– H_2O (30 : 70–45 : 55, v/v) to obtain **5** (12.5 mg, 33.5 min). Fraction I-12-6-2 (0.15 g) was purified using a preparative C_{18} HPLC column with a gradient of MeCN– H_2O (40 : 60–55 : 45, v/v) to obtain **1** (2.4 mg, 69.3 min), **2** (9.1 mg, 50.2min) and **4** (9.8 mg, 27.4 min). Fraction I-18 (1.1g) was separated using a Sephadex LH-20 column eluted with MeOH. Five subfractions (I-18-1–I-18-5) were collected. Fraction I-18-3 (0.12g) was purified

using a preparative C₁₈ HPLC column with a gradient of MeCN–H₂O (40 : 60–55 : 45, v/v) to obtain **3** (9.1 mg, 34.8 min). Fraction II (21.5 g) was chromatographed on a C₁₈ MPLC column eluted with a gradient of MeOH–H₂O (10 : 90–100 : 0, v/v) to give the twelve subfractions II-1–II-12. Fraction II-7 (3.3g) was separated using a Sephadex LH-20 column eluted with MeOH. Eight subfractions (II-7-1–II-7-8) were collected. Fraction II-7-7 (0.09 g) was purified using a preparative C₁₈ HPLC column with a gradient of MeCN–H₂O (25 : 75–40 : 60, v/v) to obtain **6** (8.7 mg, 24.6 min).

Bousangustine A (1): yellowish amorphous powder; C₅₈H₆₄N₆O₃; [α]_D²³ –669.3 (c, 0.10, CH₃OH); UV (CH₃OH) λ_{\max} (log ϵ) 195 (4.20), 348 (2.96) nm; ¹H (400 MHz) and ¹³C (125 MHz) NMR data (methanol-*d*₄) (Table 1); positive ESIMS *m/z* 915 [M + Na]⁺. HRESIMS (*m/z* 915.4937 [M + Na]⁺, calculated for C₅₈H₆₄N₆O₃Na 915.4932).

Bousangustine B (2): yellowish amorphous powder; C₃₉H₄₄N₄O₂; [α]_D²³ –347.84 (c, 0.14, CH₃OH); UV (CH₃OH) λ_{\max} (log ϵ) 195 (4.24) nm; ¹H (400 MHz) and ¹³C (125 MHz) NMR data (methanol-*d*₄) (Table 1); positive ESIMS *m/z* 623 [M + Na]⁺. HRESIMS (*m/z* 623.3355 [M + Na]⁺, calculated for C₃₉H₄₄N₄O₂Na 623.3356).

Bousangustine C (3): yellowish amorphous powder; C₃₈H₄₂N₄O₆; [α]_D²³ –201.5 (c, 0.08, CH₃OH); UV (CH₃OH) λ_{\max} (log ϵ) 195 (3.81) nm; ¹H (400 MHz) and ¹³C (150 MHz) NMR data (methanol-*d*₄) (Table 1); positive ESIMS *m/z* 673 [M + Na]⁺. HRESIMS (*m/z* 673.2992 [M + Na]⁺, calculated for C₃₈H₄₂N₄O₆Na 673.2997).

Bioassays

The cytotoxicity of compounds **1–6** was tested using the MTS assay. The cells were seeded into 96-well tissue culture dishes at 4 × 10³ cells per well for HeLa and 5 × 10³ cells per well for SMMC-7721, HepG2, and A-549 and cultured overnight at 37 °C in a 5% CO₂ incubator for cell adhesion. Cells were then incubated in culture medium with each compound for 48 h. The MTS-reducing activity was evaluated by measuring the absorbance at 490 nm using a Cell Titer 96 A Queous One Solution Cell Proliferation Assay kit (Promega, USA) and an Infinite M200 Pro (Tecan, Austria) microplate reader. IC₅₀ values were calculated using the Reed–Muench method.

Conflicts of interest

There are no conflicts to declare.

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