Cimifrigines A–G, cytotoxic triterpenes with an oxime group from the flowers of *Cimicifuga frigida*

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Seven new dahurinol-type triterpene derivatives, including three aglycones, cimifrigines A–C (1–3), and four glycosides, cimifrigines D–G (4–7), were purified from the flowers of *Cimicifuga frigida*. These triterpenoids are characterized by an oxime group at C-15. Spectroscopic analyses and X-ray crystallography were used to determine the new structures. In the in vitro cytotoxicity screening, glycosides (4–7) exhibited more noticeable activities than the aglycones (1–3) against human HL-60, SMMC-7721, A549, MCF-7, and SW-480 cell lines. Interestingly, compounds 5 and 7, bearing a 2'-O-acetyl moiety on the sugar unit, showed comparable cytotoxicities to the positive control, cisplatin (IC_{50}: 0.5 to 5.4 μM). Whereas, analogues 4 and 6, without the 2'-O-acetyl group, indicated weaker activities with IC_{50} values ranging from 8.9 to 14.3 μM.

Introduction

Plants of the *Cimicifuga* genus (Ranunculaceae) are time-honored herbal medicines worldwide.\(^1\)–\(^3\) *C. racemosa*, namely black cohosh, is a popular food supplement in Europe and the United States for relief of menopausal disorders.\(^4\)–\(^5\) In East Asia, several *Cimicifuga* spp., for instance, *C. foetida*, *C. dahurica*, *C. heracleifolia*, *C. simplex*, and *C. japonica*, have been used to alleviate fever, pain, and inflammation since ancient times.\(^6\)–\(^7\)

Extensive efforts have been attracted to investigate chemical constituents of this genus. 9,19-Cycloartane triterpenoids (CTs) is the major chemical component of *Cimicifuga* spp. and more than 300 CTs\(^2,\)\(^7\)–\(^27\) have been reported (among them, our research group reported over 100 ones\(^2,\)\(^8\)–\(^24\)). Pharmaceutical studies revealed these CTs possessed various bioactivities, for instance, antioestperotic,\(^28\) cytotoxicity,\(^2,\(^14\)\) anti-AIDS,\(^29\) anti-Alzheimer,\(^30\) and immunosuppression.\(^31\) Nevertheless, aforementioned CTs were mainly from the rhizomes or roots of *C. racemosa*, *C. foetida*, *C. dahurica*, *C. heracleifolia*, and *C. simplex*.\(^7\)–\(^27\) Therefore, we carried out successive investigations on the roots, aerial parts, and fruits of this plant, was considered as an anti-angiogenic leadng structure. It showed comparable in vitro and ex vivo activities to those of a first-line clinical medicine, sunitinib.\(^7\) Therefore, aforementioned studies exemplified that expansion of research objects in genus *Cimicifuga* may lead to discovery of novel active CTs.

The taxonomic treatment of the Sino-Himalayan species *C. frigida* has a very long and controversial history.\(^32,\)\(^33\) However, recent cytological evidence showed that this plant is the only tetraploid (2n = 32) currently known in the genus, which together with morphological features confirmed its independent species status.\(^34\) Thus, it is of interest to explore whether there are novel bioactive compounds in this plant. In the present study, we initially carried out a study on the flowers of *C. frigida* from Litang County, Sichuan Province. Consequently, seven new 9,19-cycloartane triterpene derivatives (Fig. 1), cimifrigines A–G (1–7), were isolated. Their structures were elucidated by the help of MS, NMR, and single-crystal X-ray diffraction techniques. The unique characteristic of these analogues is that containing an oxime group at C-15 based on the dahurinol-skeleton. In addition, the isolated compounds showed potent to weak cytotoxicities against human HL-60, SMMC-7721, A549, MCF-7, and SW-480 cell lines.

Results and discussion

Cimifrigine A (1), purified as colorless crystals. The HREIMS ion peak at m/z 559.3864 [M]+ (calcd 559.3873) determined its molecular formula as C_{35}H_{35}NO_{5}, requiring 8 double-bond equivalents. The ^2H NMR spectrum (Table 1) showed characteristic cyclopropane methylene signals at δH 0.29 and 0.52 (each 1H, brs), a secondary methyl signal at δH 0.88 (d, J = 5.9
Hz), five tertiary methyl groups at $\delta_H$ 1.04–1.59, and an active hydrogen signal at $\delta_H$ 12.32, respectively. In the $^{13}$C NMR spectrum (Table 2), an olefing (or a carbonyl) carbon signal at $\delta_C$ 164.34 (C-15), and five oxygenated carbons at $\delta_C$ 78.01 (C-3, d), 80.55 (C-16, d), 78.76 (C-23, d), 77.13 (C-24, d), and 77.53 (C-25, s) were also observed. Aforementioned data suggested that 1 was a highly oxygen-bearing 9,19-cycloartane triterpenoid with a six-ring carbon skeleton.

Study of the $^1$H–$^1$H COSY (Fig. 2) spectrum of 1 revealed the existence of partial structures C1/C-2/C3 (–CH$_2$–CH$_2$–CH$_3$), C-5/C-6/C-7/C8 (–CH$_2$CH$_2$CH$_2$CH$_3$), C-11/C-12 (–CH$_2$CH$_2$–), and C-16/C-17/C-20 (C-21)/C-22/C-23 (–CHCHCH(CH$_3$)CH$_2$CH$_3$–), which consistent with typical rings A–E of a dahurinol-type triterpene.$^{11,13,15,16}$ Based on HMBC correlation from H-16 at $\delta_H$ 4.24 to the oxygenated methine at $\delta_C$ 78.76 (C-23), and the existence of the spin system C-16/C-17/C-20/C-21/C-22/C-23, the ring E was established as shown.$^1$H–$^1$H COSY association between H-23 ($\delta_H$ 4.11) and H-24 ($\delta_H$ 5.34) indicated the linkage of C-23 and C-24. In addition, the connection of C-24 and C-25 was elucidated from the HMBC correlation of H-24 (brs) and the active hydrogen ($\delta_H$ 12.32) to C-14 ($\delta_C$ 51.67) and C-15 ($\delta_C$ 164.34), which confirmed the configuration of C-24 of 1 was deduced as S (the coupling constants of H-24 of dahurol-type compounds is around 6–9 Hz).$^{11,13,15,16}$ Finally, X-ray diffraction analysis (Fig. 3) allowed to confirm the oxime group at C-15, the relative configurations, and the stereochemistry of 1 at C-24 of 1 due to the Hooft parameter 0.13(8) for 1536 Bijvoet pairs.$^{37}$ Therefore, the structure of 1 was constructed as shown.

The molecular formulas of cimifrigines B (2) and C (3) were determined as C$_{32}$H$_{52}$NO$_6$ and C$_{31}$H$_{51}$NO$_5$ by the HREIMS [M]$^+$ m/z 545.3723, caled 545.3716, and [M]$^+$ m/z 517.3767, caled 517.3767, respectively). The NMR spectra (Tables 1 and 2) of 2 and 3 resembled to those of 1. The main differences were the substituent groups at C-25 and C-24, respectively. For compound 2, the methoxy group was replaced by a hydroxyl group at C-25. This elucidation was supported by 14 Da less of the molecular weight of 2, and the upfield shift of C-25 by 4.42 ppm. Therefore, a hydroxyl group instead of an acetoxyl unit at C-24 in compound 3 was determined by similar analyses. ROESY associations of H-3/
Table 1  

| Position | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|----------|---|---|---|---|---|---|---|
| 1        | 1.52<sup>a</sup> | 1.57 m | 1.55 m | 1.54 m | 1.52 m | 1.58 m | 1.51 m |
| 2        | 1.12<sup>a</sup> | 1.21<sup>a</sup> | 1.18<sup>a</sup> | 1.50 m | 1.15<sup>a</sup> | 1.23 m | 1.16 m |
| 3        | 1.96 m | 2.02 m | 1.97 m | 2.36 m | 2.29 m | 2.42 m | 2.27 m |
| 4        | 1.82 m | 1.91 m | 1.89 m | 1.94 m | 1.87 m | 1.99 m | 1.87 m |
| 5        | 3.51 m | 3.57 dd (11.2, 3.4) | 3.54 m | 3.49 dd (11.6, 4.2) | 3.39 dd (11.6, 4.4) | 3.54 dd (11.6, 4.3) | 3.37 dd (11.2, 3.8) |
| 6        | 1.27 m | 1.31 dd (12.4, 4.1) | 1.32 dd (12.5, 4.3) | 1.30 dd (12.6, 4.3) | 1.30 dd (12.4, 4.1) | 1.37 dd (12.5, 4.2) | 1.31 m |
| 7        | 1.52<sup>a</sup> | 1.56 m | 1.79<sup>a</sup> | 1.50 m | 1.51 m | 1.59 m | 1.55 m |
| 8        | 0.71 m | 0.73 q (12.7) | 0.76 m | 0.65 q (12.4) | 0.68 q (12.7) | 0.75 q (12.5) | 0.73 m |
| 9        | 2.54 m | 2.57 m | 2.60 m | 2.53 m | 2.55 m | 2.60 m | 2.59 m |
| 10       | 1.01<sup>a</sup> | 1.07<sup>a</sup> | 1.08<sup>a</sup> | 1.10<sup>a</sup> | 1.02 m | 1.13 m | 1.08<sup>a</sup> |
| 11       | 1.82 m | 1.84 m | 1.86 m | 1.80 m | 1.80 m | 1.87 dd (12.6, 3.3) | 1.84 m |
| 12       | 1.99 m | 2.04 m | 2.03 m | 1.98 m | 1.97 m | 2.05<sup>a</sup> | 2.00<sup>a</sup> |
| 13       | 1.03<sup>a</sup> | 1.07<sup>a</sup> | 1.06<sup>a</sup> | 1.10<sup>a</sup> | 0.99 m | 1.05<sup>a</sup> | 1.00 m |
| 14       | 1.52<sup>a</sup> (2H) | 1.58 m (2H) | 1.55 m (2H) | 1.54 m (2H) | 1.62 m (2H) | 1.58 m (2H) |

**Table 1** <sup>a</sup> Signals overlapped.

H5, H16/CH$_3$-18, H20/CH$_3$-18 and H16/H23 both in 2 and 3 suggested the z, β, β, and β orientations of H-3, H-16, H-20, and H-23, respectively. The S configuration of C-24 of 2 and 3 was proposed by the same way as that of 1. Accordingly, the structures of 2 and 3 were established as shown.

Cimifugine D (4) had the molecular formula C$_{13}$H$_{23}$NO$_{10}$ as determined by HREIMS (m/z 677.4129 [M]$^+$, cale 677.4139). In the $^1$H NMR spectrum, resonances for an anomic proton at $\delta_H$ 4.79 (H-1′, 1H, $d, J = 7.1$ Hz), and a cyclopropane methylene at $\delta_H$ 0.20 (6H, $d, J = 3.9$ Hz) and 0.48 (1H, d, $J = 3.3$ Hz) were observed. These data indicated 4 was a 9,19-cycloartenol triterpene substituted with a sugar unit. Analyses of NMR spectroscopic data revealed that, structurally, the aglycone part of 4 was identical to 2. The sugar unit in 4 was located to C-3 on the basis of HMBC correlation between the anomic proton at $\delta_H$ 4.79 ($J = 7.1$ Hz) and the methine signal at $\delta_C$ 88.59 (C-3). In addition, by comparing its TLC and specific rotation with a standard after acid hydrolysis, the sugar was determined as L-arabinose. ROESY
correlations of H-16/CH$_3$-18, H-20/CH$_3$-18 and H-16/H-23 suggested an $\alpha$-orientation of the substituents at C-16, C-20 and C-23, respectively. Whereas, a $\beta$-orientation of the substituent at C-3 was established by the cross-peak of H-3/H-5. The configuration of C-24 was proposed as S by the same way as that of 1. Therefore, the structure of 4 was elucidated as shown.

| Position | 1     | 2     | 3     | 4     | 5     | 6     | 7     |
|----------|-------|-------|-------|-------|-------|-------|-------|
| 1        | 33.96 CH$_2$ | 33.29 CH$_2$ | 32.92 CH$_2$ | 32.70 CH$_2$ | 32.57 CH$_2$ | 32.64 CH$_2$ | 32.57 CH$_2$ |
| 2        | 31.53 CH$_2$ | 31.98 CH$_2$ | 31.47 CH$_2$ | 30.09 CH$_2$ | 30.44 CH$_2$ | 30.14 CH$_2$ | 29.98 CH$_2$ |
| 3        | 78.01 CH   | 78.37 CH   | 78.00 CH   | 88.59 CH   | 89.07 CH   | 88.51 CH   | 88.69 CH   |
| 4        | 41.16 C    | 41.58 C    | 41.14 C    | 41.35 C    | 41.47 C    | 41.34 C    | 41.06 C    |
| 5        | 47.69 CH   | 47.99 CH   | 47.67 CH   | 47.78 CH   | 48.02 CH   | 47.71 CH   | 47.67 CH   |
| 6        | 21.70 CH$_2$ | 21.99 CH$_2$ | 21.42 CH$_2$ | 21.38 CH$_2$ | 21.76 CH$_2$ | 21.37 CH$_2$ | 21.42 CH$_2$ |
| 7        | 26.98 CH$_2$ | 27.36 CH$_2$ | 22.08 CH$_2$ | 26.84 CH$_2$ | 26.12 CH$_2$ | 26.68 CH$_2$ | 26.90 CH$_2$ |
| 8        | 46.43 CH   | 46.74 CH   | 46.34 CH   | 46.33 CH   | 46.70 CH   | 46.21 CH   | 46.26 CH   |
| 9        | 20.06 C    | 20.38 C    | 20.02 C    | 20.03 C    | 20.46 C    | 19.98 C    | 20.13 C    |
| 10       | 27.16 C    | 27.59 C    | 26.99 C    | 26.84 C    | 27.25 C    | 26.85 C    | 26.70 C    |
| 11       | 25.83 CH$_2$ | 26.30 CH$_2$ | 25.75 CH$_2$ | 25.66 CH$_2$ | 26.02 CH$_2$ | 25.35 CH$_2$ | 25.62 CH$_2$ |
| 12       | 30.99 CH$_2$ | 31.26 CH$_2$ | 30.94 CH$_2$ | 30.89 CH$_2$ | 31.21 CH$_2$ | 30.83 CH$_2$ | 30.93 CH$_2$ |
| 13       | 42.50 C    | 43.01 C    | 42.44 C    | 42.48 C    | 42.85 C    | 42.61 C    | 42.52 C    |
| 14       | 51.67 C    | 51.93 C    | 51.65 C    | 51.62 C    | 51.98 C    | 51.62 C    | 51.71 C    |
| 15       | 164.34 C   | 164.63 C   | 164.64 C   | 164.30 C   | 164.53 C   | 164.37 C   | 164.50 C   |
| 16       | 80.55 CH   | 81.17 CH   | 80.09 CH   | 80.42 CH   | 80.83 CH   | 80.25 CH   | 80.55 CH   |
| 17       | 54.60 CH   | 54.61 CH   | 54.66 CH   | 54.36 CH   | 54.70 CH   | 54.88 CH   | 54.99 CH   |
| 18       | 19.86 CH$_2$ | 20.36 CH$_2$ | 19.83 CH$_1$ | 19.77 CH$_3$ | 20.27 CH$_3$ | 19.80 CH$_3$ | 19.86 CH$_3$ |
| 19       | 31.44 CH$_2$ | 31.85 CH$_2$ | 31.42 CH$_2$ | 31.36 CH$_2$ | 31.62 CH$_2$ | 31.20 CH$_2$ | 31.19 CH$_2$ |
| 20       | 32.28 CH   | 33.48 CH   | 33.23 CH   | 33.18 CH   | 33.57 CH   | 32.85 CH   | 32.93 CH   |
| 21       | 20.09 CH$_2$ | 20.38 CH$_2$ | 20.17 CH$_1$ | 19.93 CH$_3$ | 20.40 CH$_3$ | 20.08 CH$_3$ | 20.13 CH$_3$ |
| 22       | 39.18 CH$_2$ | 38.74 CH$_2$ | 39.94 CH$_2$ | 38.83 CH$_2$ | 39.14 CH$_2$ | 38.16 CH$_2$ | 38.26 CH$_2$ |
| 23       | 78.76 CH   | 80.00 CH   | 78.59 CH   | 78.77 CH   | 79.17 CH   | 81.89 CH   | 82.01 CH   |
| 24       | 77.13 CH   | 79.07 CH   | 78.34 CH   | 80.25 CH   | 80.65 CH   | 78.74 CH   | 78.82 CH   |
| 25       | 77.53 C    | 73.11 C    | 78.18 C    | 74.15 C    | 74.79 C    | 146.53 C   | 146.57 C   |
| 26       | 23.21 CH$_2$ | 28.86 CH$_3$ | 23.08 CH$_3$ | 29.57 CH$_3$ | 30.08 CH$_3$ | 113.13 CH$_3$ | 113.18 CH$_3$ |
| 27       | 21.70 CH$_1$ | 27.73 CH$_1$ | 20.42 CH$_1$ | 29.57 CH$_1$ | 29.97 CH$_1$ | 18.55 CH$_1$ | 18.59 CH$_1$ |
| 28       | 19.56 CH$_1$ | 20.59 CH$_1$ | 19.39 CH$_1$ | 19.55 CH$_1$ | 20.07 CH$_1$ | 19.29 CH$_1$ | 19.34 CH$_1$ |
| 29       | 14.89 CH$_2$ | 15.38 CH$_2$ | 15.25 CH$_2$ | 15.39 CH$_2$ | 15.69 CH$_2$ | 15.36 CH$_2$ | 15.25 CH$_2$ |
| 30       | 26.19 CH$_1$ | 26.62 CH$_1$ | 25.46 CH$_1$ | 25.75 CH$_3$ | 25.89 CH$_3$ | 25.67 CH$_3$ | 25.46 CH$_3$ |

3-Ara

1' 107.36 CH
2' 105.01 CH
3' 74.83 CH
4' 74.37 CH
5' 72.89 CH

24-OCH$_3$ 170.83 C
24-OCOCH$_3$ 21.05 CH$_3$

25-OCH$_3$ 49.27 CH$_3$
2'-OCH$_3$ 49.23 CH$_3$
2'-OCOCH$_3$ 171.14 C

Fig. 2 Major HMBC ( ), $^1$H--$^1$H COSY ( ), and ROESY ( ) correlations of compound 1.
The spectroscopic features of cimifrigines F (6) and G (7) resembled to each other except for the sugar unit. The molecular formulas of 6 and 7 were determined as C_{36}H_{55}NO_{11} and C_{37}H_{57}NO_{9}, respectively, by HREIMS ([M]+ m/z 617.3943, caleld 617.3928, and [M]+ m/z 659.4053, caleld 659.40337, respectively). Same to that of compounds 4 and 5, the molecular weight difference between 6 and 7 was 42 Da, which equivalent to an acetyl moiety. In addition, the acetoxy group in 7 was located to C-2' based on the HMBC correlation of the acetoxy methyl group (δ_H 2.11) and C-2' (δ_C 74.37). Structurally, the aglycone part of 6 and 7 was similar to that of 2 except that a terminal double bond was formed between C-25 and C-26 in 6 and 7. HMBC correlations from the olefinic protons at δ_H 5.30 (for 6) and 5.27 (for 7) and δ_H 5.04 (for 6) and 5.01 (for 7) to C-24 (δ_C 78.74 for 6 and 78.82 for 7), C-25 (δ_C 146.53 for 6 and 146.57 for 7), and CH_{3}-27 (δ_C 18.55 for 6 and 18.59 for 7) further supported this elucidation. The sugar obtained after acid hydrolysis was identified as L-arabinose by comparing its TLC and specific rotation with a standard. The α-orientation of the substituents at C-16, C-20 and C-23 were determined by ROESY correlations of H-16/H-21, H-20/H_{21-18}, H-20/CH_{3}-18 and H-16/H-23. Whereas, correlation of H-3/H-5 indicated the β-orientation of the substituent at C-3. The coupling constant of H-24 for 6 and 7 was 6.3 Hz which consistent with those of dahurinyl-type compounds (6–9 Hz).\textsuperscript{11,13,15,36} Thus, the stereochemistry of C-24 was elucidated as S and the structure of 6 and 7 were determined as shown.

Cimifrigines A–G (1–7) were evaluated against human HL-60, SMMC-7721, A549, MCF-7, and SW-480 cell lines for their cytotoxicities. All compounds (1–7) showed different levels of activities with the glycoside derivatives (4–7) stronger than the aglycone analogues (1–3) (Fig. 4, Table S1†). Compounds 5 and 7 exhibited as potent activities as positive control cisplatin (IC_{50}: 0.5 to 5.4 μM) against all cell lines with IC_{50} values ranging from 0.8 to 6.3 μM. However, 4 and 6 indicated broad spectrum and moderate activities with IC_{50} values around 8.9 to 14.3 μM. Structurally, the C-2’ position was substituted by an acetoxy unit in 5 and 7. While, a hydroxy group was located at this position in 4 and 6. Therefore, based on the aforementioned data, it may gave the preliminary conclusion that sugar unit is critical to the cytotoxicities of this new type of CTs. Besides, hydrophobic groups like acetoxy at the sugar unit could enhance the activities as much as one order of magnitude.

**Conclusions**

As mentioned in the Introduction besides the roots of *Cimicifuga* spp., nontraditionally used part, such as fruits, also contained novel active CTs. Therefore, we expanded the research target to the flowers of *C. frigida*, a species of which the chemical constituents have not been reported yet. As a result, seven new dahurinyl-type analogues, cimifrigines A–G (1–7), with an oxime group at C-15, were isolated and identified. Significantly, all of the compounds had cytotoxic effect and two of them showed comparable activity as that of cisplatin, the positive control, in the in vitro cytotoxicity assay. Besides, preliminary structure–activity relationship also discussed in the study which afforded potential informations for further chemical
Experimental section

General experimental procedures

Column chromatography (CC) was run on silica gel (200–300 mesh, Qingdao Marine Chemical, Inc.), and Lichroprep RP-18 (46–63 μm, Merck). Semi-preparative HPLC was carried out on an Agilent 1100 liquid chromatography system using an YMC-Pack 10 mm × 250 mm column (Pro C18 RS). Precoated TLC plates (200–250 μm thickness, silica gel 60 F254, Qingdao Marine Chemical, Inc.) were used for thin-layer chromatography. The spots in TLC were visualized by heating after spraying with 10%aq. H2SO4. 1D and 2D NMR spectra were performed on Bruker DRX-500 and Avance III-600 MHz spectrometers (Bruker, Zürich, Switzerland) with solvent signal as internal reference. ESIIMS and HRESIMS were run on a Shimadzu LCMS-IT-TOF mass spectrometer (Shimadzu, Kyoto, Japan) or an Agilent G6230 TOF MS (Agilent Technologies, Palo Alto, USA). Infrared spectrometry was tested on a Shimadzu IR-450 instrument with KBr pellets. A JASCO P-1020 digital polarimeter was applied to record optical rotations, using MeOH as solvent. X-ray diffraction was realized on a Bruker SMART APEX CCD crystallography system.

Plant material

The flowers of *Cimicifuga frigida* (1.0 kg) were collected from Litang County, Sichuan Province, China, in September 2012. Prof. Wang Zongyu, Kunming Institute of Botany, Chinese Academy of Sciences, identified the species. A voucher specimen (KUN no. 2012090033) has been deposited at the State Key Laboratory of Phytochemistry and Plant Resources in West China, Kunming Institute of Botany, Chinese Academy of Sciences, PR China.

Extraction and isolation

MeOH (4 L, 3 times, 7 days each) was extracted to obtain the dried and milled flowers of *Cimicifuga frigida* (1.0 kg) at room temperature. MeOH was evaporated under vacuum at 50 °C to afford the extract (87.4 g). The extract gave fractions A (10.3 g), B (18.1 g), C (13.4 g), and D (12.3 g) by silica gel CC (2.5 kg, 10 × 150 cm) eluted with CHCl3–MeOH [100 : 0 (4 L), 50 : 1 (8 L), 10 : 1 (7 L), 0 : 100 (4 L)]. Another six sub-fractions (B.1–B.6) were obtained through RP-18 CC (500 g, 6 × 50 cm), gradient eluted with MeOH–H2O from 60 : 40 to 100 : 0. Fraction B.3 (2.7 g) yielded compounds 1 (3.8 mg), 2 (3.2 mg), and 3 (1.9 mg) by silica gel CC (40 g, 3 × 60 cm) eluting with CHCl3–MeOH from 30 : 1 gradient to 10 : 1 and semi-preparative HPLC [eluited with CHCl3–MeOH, gradient from 65 : 35 to 85 : 15]. Sub-fractions (C.1–C.4) were obtained by RP-18 CC [eluited with MeOH–H2O, gradient from 50 : 40 to 85 : 15] on fraction C. Consequently, 5 (3.3 mg), and 7 (2.8 mg) were purified from fraction C.2 (1.8 g) by silica gel CC (40 g, 3 × 40 cm) eluted with CHCl3–MeOH [gradient from 20 : 1 to 10 : 1], and then repeated semi-preparative HPLC [eluited with CH3CN–H2O, gradient from 50 : 50 to 65 : 35]. Fraction C.3 gave compounds 4 (2.5 mg) and 6 (2.7 mg) by successively silica gel CC (40 g, 3 × 40 cm, eluted with CHCl3–MeOH 10 : 1, 13 L), and semi-preparative HPLC [eluited with CH3CN–H2O, gradient from 50 : 50 to 65 : 35].

(3β,16S,23R,245S)-16,23-epoxy-3-hydroxy-15-oximido-24-acetoxy-25-methoxy-9,19-cycloartane (1). Colorless crystals; [α]25D = +38.9 (c 0.09, MeOH); mp 315–317 °C; IR (KBr): rmax 3438, 2967, 2867, 1740, 1628, 1456, 1374, 1241, 1068, 926 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150 MHz, C2D2N) data; positive ESIMS [M + Na]+ m/z 582; positive HREIMS [M]+ m/z 559.3864 (calcd for C33H53NO6, 559.3873).

(3β,16S,23R,245S)-16,23-epoxy-3,25-dihydroxy-15-oximido-24-acetoxy-9,19-cycloartane (2). White powder; [α]25D = −2.1 (c 0.03, MeOH); IR (KBr): rmax 3442, 2932, 2869, 1734, 1631, 1452, 1384, 1248, 1098, 1028 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150 MHz, C2D2N) data; positive ESIMS [M + Na]+ m/z 540; positive HREIMS [M]+ m/z 545.3723 (calcd for C31H51NO5, 545.3716).

(3β,16S,23R,245S)-16,23-epoxy-3,24-dihydroxy-15-oximido-24-acetoxy-9,19-cycloartane (3). White powder; [α]25D = +30.1 (c 0.10, MeOH); IR (KBr): rmax 3397, 2928, 2865, 1724, 1632, 1459, 1376, 1144, 1081, 927 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150 MHz, C2D2N) data; positive ESIMS [M + Na + H2O]+ m/z 718; positive HREIMS [M]+ m/z 717.3776 (calcd for C31H53NO8, 717.3767).

(3β,16S,23R,245S)-16,23-epoxy-3,24-dihydroxy-15-oximido-24-acetoxy-9,19-cycloartane (4). White powder; [α]25D = +38.4 (c 0.09, MeOH); IR (KBr): rmax 3423, 2928, 2870, 1745, 1630, 1459, 1375, 1232, 1085, 1020, 937 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150 MHz, C2D2N) data; positive ESIMS [M + Na + H2O]+ m/z 718; positive HREIMS [M]+ m/z 717.4129 (calcd for C39H63NO12, 717.4139).

(3β,16S,23R,245S)-16,23-epoxy-15-oximido-24-acetoxy-25-hydroxy-19-cycloartane-3-0-α-L-arabinopyranoside (5). White powder; [α]25D = +28.1 (c 0.09, MeOH); IR (KBr): rmax 3441, 2935, 2870, 1744, 1629, 1456, 1374, 1232, 1084, 936 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150 MHz, C2D2N) data; positive ESIMS [M + Na + H2O]+ m/z 760; positive HREIMS [M]+ m/z 719.4281 (calcd for C35H55NO8, 719.4245).

(3β,16S,23R,245S)-16,23-epoxy-15-oximido-24-acetoxy-25-hydroxy-19-cycloartane-3-0-α-L-arabinopyranoside (6). White powder; [α]25D = +10.2 (c 0.06, MeOH); IR (KBr): rmax 3450, 2930, 2868, 1630, 1454, 1378, 1250, 1068, 1010, 973 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150 MHz, C2D2N) data; positive ESIMS [M + Na]+ m/z 640; positive HREIMS [M]+ m/z 617.3943 (calcd for C35H55NO8, 617.3928).

(3β,16S,23R,245S)-16,23-epoxy-15-oximido-24-acetoxy-25-en-9,19-cycloartane-3-0-α-L-arabinopyranoside (7). White powder; [α]25D = +15.0 (c 0.06, MeOH); IR (KBr): rmax 3424, 2935, 2869, 1737, 1628, 1454, 1377, 1249, 1069, 1019, 935 cm−1; see Tables 1 and 2 for 1H NMR (500 MHz, C2D2N) and 13C NMR (150
MHZ, C2D2N data; positive ESIMS [M + Na]+ m/z 682; positive HREIMS [M]+ m/z 659.4053 (calcd for C32H57NO3, 659.4033).

X-ray crystal structure analysis
A Bruker APEX DUO diffractometer equipped with an APEX II CCD was used to obtain the intensity data at 100 K, using Cu Kα radiation. Bruker SAINT was applied for cell refinement and data reduction. The structure was determined by direct methods using SHELXS-97.38 Refinements were performed with SHELXL-97, using full-matrix least-squares, with anisotropic displacement parameters for all the non-hydrogen atoms. The H atoms were placed in calculated positions and refined using a riding model. Molecular graphics were calculated with PLATON.

X-ray crystallography of compound 1
Colorless crystals of compound 1 (CCDC: 1545247†) was obtained by methanol extract of Cimicifuga frigida. The X-ray crystallographic data of 1: C13H25NO8, monoclinic, space group P21, a = 9.5634(4) Å, b = 11.2799(5) Å, c = 14.9190(6) Å, α = 90.00(3), β = 103.4570(10), γ = 90.00(3), V = 1565.19(11) Å3, Z = 2, Dcalc = 1.188 g cm⁻³. The final R1 values were 0.0706 (I > 2σ(I)). The final wR2(F2) values were 0.2898 (I > 2σ(I)). The goodness of fit on F² was 1.492. Crystal size, 0.54 × 0.40 × 0.10 mm². Flack parameter = 0.2(3). The Hoof parameter is 0.13(8) for 1536 Bijvoet pairs.

Hydrolysis and identification of the sugar units in compounds 4–7
The MeOH solution (3 mL) of each compound (1.5 mg) was refluxed with 0.5 N HCl (2 mL) for 2 h. CHCl₃ (3 × 10 mL) was used to extract the reaction mixture after diluting with H₂O. A monosaccharide was given by neutralizing each aqueous layer with Ag₂CO₃ and filtering the precipitate. The monosaccharide from compounds 4–7 had an Rx (EtOAc–CHCl₃–MeOH–H₂O, 3 : 2 : 2 : 1) and specific rotation of [α]D 20 +63.4 (c 0.06, MeOH) corresponding to those of L-arabinose (Sigma-Aldrich).

Cytotoxicity bioassay
The human tumor cell lines HL-60, SMMC-7721, A549, MCF-7, and SW-480 were used in the cytotoxic assay. These cell lines were obtained from ATCC (Manassas, VA, USA). DMEM medium (HyClone, USA) supplemented with 10% fetal bovine serum (HyClone, USA) was used to culture cells in 5% CO₂ at 37 °C. The MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide) method was applied to evaluate the cytotoxicity.39,40 Briefly, cells were seeded into each well of a 96-well cell culture plate. After 12 h of incubation at 37 °C, the test compound was added. Each tumor cell line was exposed to compounds 1, 2, and 3 at concentrations of 3, 10, 20, 50, and 100 μM triplicates for 48 h, to compounds 4 and 6 at concentrations of 1, 3, 10, 30, and 50 μM triplicates for 48 h, and to compounds 5 and 7 at concentrations of 0.1, 0.3, 1, 5, 10, and 20 μM triplicates for 48 h, respectively. Cisplatin (Sigma, USA) was used as a positive control. After compound treatment, cell viability was detected and a cell growth curve was graphed. IC₅₀ values were calculated by Reed and Muench’s method.41 (All compounds were dissolved in DMSO as 100 mM stock and 0.1% DMSO was used as the solvent).

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