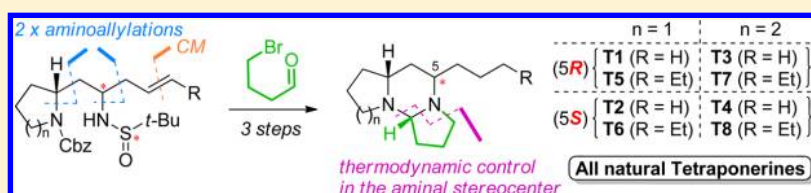


Natural Tetraponerines: A General Synthesis and Antiproliferative Activity

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S Supporting Information



ABSTRACT: A stereocontrolled general methodology to access all natural tetraponerines from (+)-T1 to (+)-T8 is detailed. Two consecutive indium-mediated aminoallylations with the appropriate enantiomer of chiral *N*-*tert*-butylsulfinamide and a thermodynamic control at the aminal stereocenter allow the formation of each natural tetraponerine with excellent stereoselectivity. The use of 4-bromobutanal in the first aminoallylation leads to the formation of 5–6–5 tetraponerines, while 5-bromopentanal is required to build the scaffold of 6–6–5 tetraponerines. A cross-metathesis reaction of the second aminoallylation product with *cis*-3-hexene is used to elongate the side chain up to 5 carbons so as to prepare the tetraponerines T5 to T8. The anticancer activity of these heavier tetraponerines against four different carcinoma human cell lines is examined, observing a promising cytotoxic activity of (+)-T7 against breast carcinoma cell line MCF-7.

INTRODUCTION

Azaheterocycles with nitrogen atoms at the junction of two rings constitute a large group of natural alkaloids that commonly exhibit a quinolizidine or an indolizidine framework and display a wide range of biological activities.¹ The complexity of these compounds is further increased by the stereochemistry of the pyramidal nitrogen at the ring junction, with important consequences in their bioactivities.² Tetraponerine alkaloids form a unique family of such compounds, which share a quinolizidine or an indolizidine fragment with another indolizidine framework. These tricyclic alkaloids, named tetraponerines T1 to T8, possess a very uncommon aminal structure in alkaloids³ and can be divided in two groups depending on the size of the rings: 5–6–5 or 6–6–5. In each group, the tetraponerines differ in the length of the alkyl chain located in C₅ (propyl or pentyl) and in the configuration of this stereocenter (Figure 1).

Tetraponerines are secreted by *Pseudomyrmecine* ants of the genus *Tetraponera*, for which more than 80 species can be found in Asia, Africa, or Australia; T8 is the major tetraponerine isolated from the New Guinean ant *Tetraponera*, while T1 and T2 are very minor naturally occurring products. It was early recognized that tetraponerines are paralyzing venoms segregated by the host ants against their enemies. Not surprisingly, it was found that they exhibit important insecticidal and neurotoxic biological activities.⁴ Recent studies categorize them as efficient inhibitors of a range of nAChRs (nicotinic

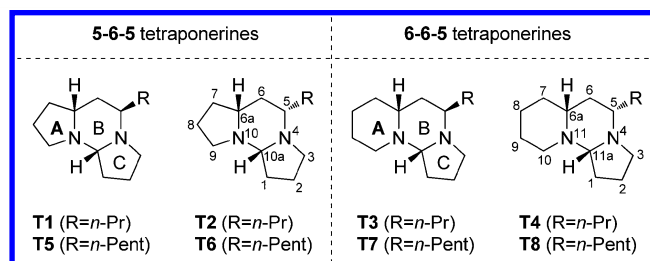


Figure 1. Structures of natural tetraponerines.

acetylcholine receptors).⁵ However, despite their interesting biological profile, the actual mechanisms of interaction with their corresponding receptors are still unknown. More recently, cytotoxic activities have also been described for these natural products as well as for some synthetic analogues containing long hydrocarbon chains at C₅ position.⁶

In 1987 Braekman and co-workers reported the first isolation and structural elucidation of these natural products.⁴ The structure of T8 was unequivocally assigned by X-ray diffraction analysis,⁴ while the structures of the other natural tetraponerines were proposed by comparison of their spectroscopical data, in particular one-dimensional ¹H and ¹³C NMR spectra, with those of T8.⁷ However, structures of T3, T5, T6, and T7 were

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mistakenly described at first and corrected then by further studies involving nuclear magnetic resonance and circular dichroism.⁸ More recently, the combined use of infrared spectroscopy (IR) and mass spectrometry (MS) have also been described to easily identify each tetraoponerine from its natural source.⁹ In this study it was observed that tetraoponerines with 5-(*S*) configuration show more intense Bohlmann bands in the infrared spectra at lower vibrational frequencies than the 5-(*R*) isomers.

The origin of natural tetraoponerines has been studied by the Braekman's group with **T6**¹⁰ and **T8**,¹¹ and different biosynthetic routes were proposed depending on the A ring size. Importantly, upon studies of its biochemical pathway, **T8** was submitted to catalytic hydrogenation under acidic conditions, and the N₁₁–C_{11a} bond was selectively cleaved, suggesting that the aminal core is in equilibrium with the corresponding iminium ion.

The first enantioselective synthesis of (+)-**T8** was achieved in 1990, providing a firm evidence of the absolute configuration of this natural alkaloid.¹² The singular tricyclic skeleton of these alkaloids, which holds an aminal moiety, along with their interesting biological activities have made the tetraoponerines very attractive targets for total synthesis.¹³ The group of Royer applied its CN (*R,S*) strategy¹⁴ to the synthesis of all natural tetraoponerines known, being the only general method reported to prepare this entire family of alkaloids up to date.¹⁵

Aware of the lack of detailed structural information on tetraoponerines we have recently examined the conformational and configurational space of **T3** and **T4**.¹⁶ For this study we fixed the known configurations at C_{6a} (*R*) and at C₅ [(*R*)- for **T3** and (*S*)- for **T4**] and considered all possible configurations at nitrogen atoms (N₄ and N₁₁) as well as at the aminal carbon center (C_{11a}). The geometry of the resulting 12 configurational isomers (for each tetraoponerine) was optimized by DFT calculations, and their populations were estimated from the calculated energies. The first conclusion from these calculations is that for both **T3** and **T4**, at least 99% of the population is represented by either its *ttc*- or *tft*- isomer (Figure 2).¹⁷ A closer

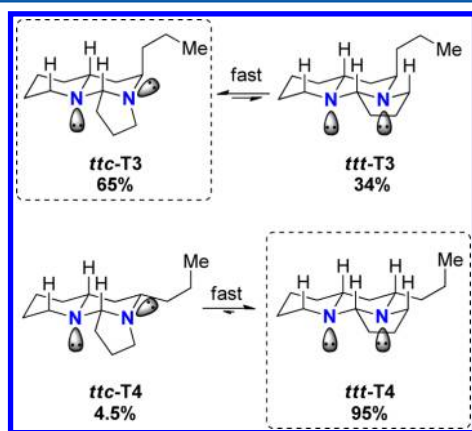


Figure 2. Main configurational isomers previously found by DFT calculations of **T3** and **T4**.¹⁶

examination of these two configurational isomers shows that, despite the different fusions at the indolizidine frameworks, the same (*S*)-configuration at the aminal carbon center is observed. Remarkably, this configuration at C_{11a} is observed not only for natural **T3** and **T4**, but also for all the other natural tetraoponerines. On the other hand, tetraoponerine **T3** slightly

prefers a *cis*-configuration at ring C (65% of *ttc*-**T3**), while **T4** is clearly dominated by a *trans*-configuration at the indolizidine framework (95% of *tft*-**T4**). Importantly, low activation barriers were found for inversion of **T3** and **T4** at N₄, which allows a fast equilibration between the two most populated isomers (*ttc* and *tft*). Interestingly, tetraoponerine analogues with a 5–5–6 tricyclic skeleton have recently been prepared in racemic form.¹⁸ The relative stereochemistry of these latter analogues was assigned as *cis* (fusion A/B)-*transoid-trans* (fusion B/C), according to NOE correlations.

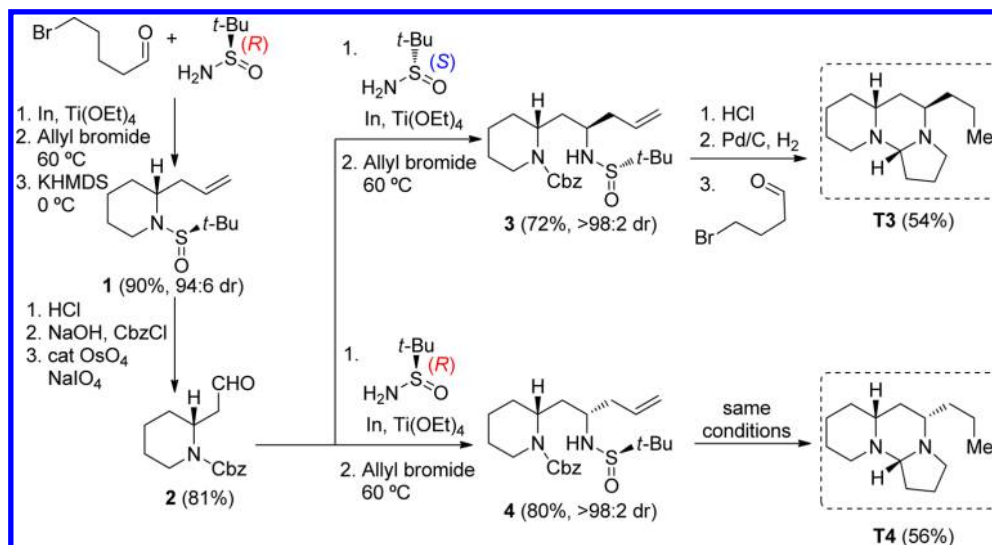
In the present work we describe a detailed account of our stereoselective total synthesis of all known tetraoponerines, from (+)-**T1** to (+)-**T8**. We also provide the anticancer activity of C₅-pentyl tetraoponerines (**T5** to **T8**) against four human cell lines.

RESULTS AND DISCUSSION

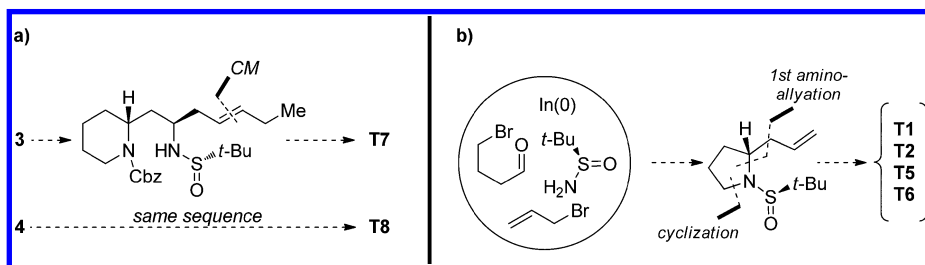
In a previous work,¹⁶ we described the total synthesis of natural tetraoponerines **T3** and **T4** using a divergent approach from simple starting materials: 4-bromobutanol, 5-bromopentanol, allyl bromide, and both enantiomeric forms of *N*-*tert*-butylsulfonamide.¹⁹ As depicted in Scheme 1, the synthesis started with a 2-allylpiperidine derivative, which was prepared by aminoallylation of 5-bromopentanol with (*R*)-*tert*-butylsulfonamide and in situ generated allylindium reagent, followed by intramolecular *N*-alkylation.²⁰ Oxidative cleavage of the double bond gave rise to the corresponding aldehyde **2**, which was submitted to a second aminoallylation where the configuration at the new stereogenic center in products **3** and **4** was mainly controlled by the chiral sulfonamide group regardless the chirality of the aldehyde.²¹ This issue was crucial to prepare the required diamines from the same chiral aldehyde, using the appropriate enantiomer of chiral *tert*-butylsulfonamide. Acidic deprotection of the homoallylic diamines, followed by hydrogenation of the allyl moiety with concomitant hydrogenolysis of the carbamate, afforded the corresponding free diamines. Without purification, these intermediates were put into react with 4-bromobutanol to initiate a cascade of reactions where the aminal formation is presumably followed by intramolecular alkylation of N₄.²² This route allowed the preparation in good overall yields of enantiomerically pure tetraoponerines (+)-**T3** and (+)-**T4** with identical spectral and physical data to the one reported in the literature for the natural compounds.⁸ Importantly, the aminal formation with the right stereochemistry at C_{11a} for both compounds clearly supports the hypothesis of a thermodynamic control to afford the most stable aminal possible through equilibration with an iminium form. This idea was essential in our synthetic plan and comes from the following observations: (a) all natural tetraoponerines are proposed to exhibit the same configuration at the aminal carbon center, regardless the configuration at C₅; (b) during the biosynthetic studies of **T8**, the C_{11a}–N₁₁ bond was selectively cleaved under hydrogenation conditions.¹¹ Moreover, our stereochemical analysis of tetraoponerines **T3** and **T4** by DFT calculations indicated that both tetraoponerines are mainly populated (>99%) by configurational isomers (*tft* and *ttc*) with (*S*)-configuration at C_{11a}.

Prompted by these results we decided to implement the appropriate modifications to use the same general strategy in the synthesis of all known natural tetraoponerines. As depicted in Scheme 2a, we recognized that the allyl group in the intermediates **3** and **4** provides a handle to enlarge the hydrocarbonated side-chain up to 5 carbon atoms by cross-metathesis with an appropriate partner. Therefore, tetraoponer-

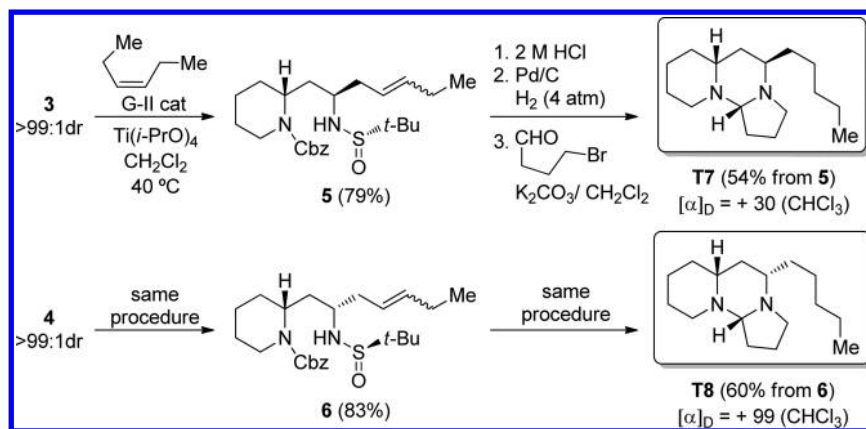
Scheme 1. Synthesis of Tetraoponerines (+)-T3 and (+)-T4



Scheme 2. Modifications for the Synthesis of the Other Tetraoponerines



Scheme 3. Synthesis of (+)-T7 and (+)-T8



ine T7 could be obtained from intermediate 3, and following the same route, compound 4 could be carried forward to the synthesis of T8. The rest of natural tetraoponerines (T1, T2, T5, and T6) have a 5-membered ring A. Accordingly, we decided to use 4-bromobutanal in our aminoallylation-cyclization sequence to prepare the key 2-allylpyrrolidine intermediate that could be submitted to the same reaction sequence followed for the synthesis of 6–6–5 tetraoponerines (Scheme 2b).

Synthesis of Tetraoponerines (+)-T7 and (+)-T8. Cross-metathesis is a very useful synthetic tool in the preparation of bioactive compounds from alkene intermediates. In this context, we²³ and others²⁴ have demonstrated that sulfinamides are tolerated by Grubbs second generation catalyst particularly when Ti(Oi-Pr)₄ is used as additive to accelerate the reaction.

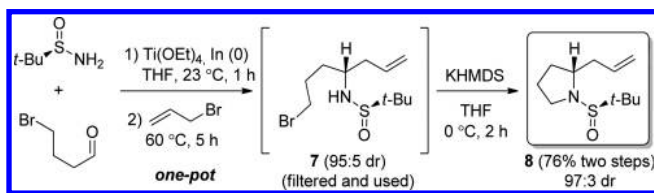
With these precedents we decided to use *cis*-3-hexene as cross metathesis partner²⁵ to elongate the side-chain up to 5 carbons of intermediates 3 and 4, en route to the preparation of T7 and T8, respectively. We were pleased to observe that the reaction took place smoothly in CH₂Cl₂ at 40 °C with both protected diamines, obtaining the expected compounds in good yields (Scheme 3).²⁶ After this single modification, the reaction sequence proceeded as for compounds T3 and T4, obtaining good overall yields and excellent diastereoselectivities (>99:1 dr by GC) for both tetraoponerines T7 and T8. NMR spectra were compared with the data of T3 and T4, finding the same signal pattern distinctive of these 6–6–5 skeletons. More importantly, the physical and spectral data of the synthesized (+)-T7

and (+)-**T8** were in full agreement with reported values for these naturally occurring compounds.^{13b,c}

Synthesis of Tetraponerines (+)-T1**, (+)-**T2**, (+)-**T5**, and (+)-**T6**.** Our next goal was to extend this methodology to the synthesis of the remaining natural 5–6–5-tetraponerines (**T1**, **T2**, **T5**, and **T6**), which differ from the others in the size of ring A. It is worth saying that this extension is not straightforward, and our DFT configurational analysis was only performed for tetraponerines **T3** and **T4**, with a 6–6–5 pattern. The subgroup of tetraponerines with two indolizidine moieties fused in the core has a more flexible scaffold, and the contribution of several configurational isomers could complicate the stereochemical landscape of these compounds. This issue has been so far overlooked in the literature.

Our synthesis began with the indium-mediated amino-allylation of 4-bromobutanal with (*R*_S)-*tert*-butylsulfinamide, followed by cyclization with KHMDS at 0 °C. The corresponding 2-allylpyrrolidine **8** was obtained in good diastereoselectivity and good overall yield after only one purification step (Scheme 4).

Scheme 4. Synthesis of 2-Allylpyrrolidine Intermediate 8

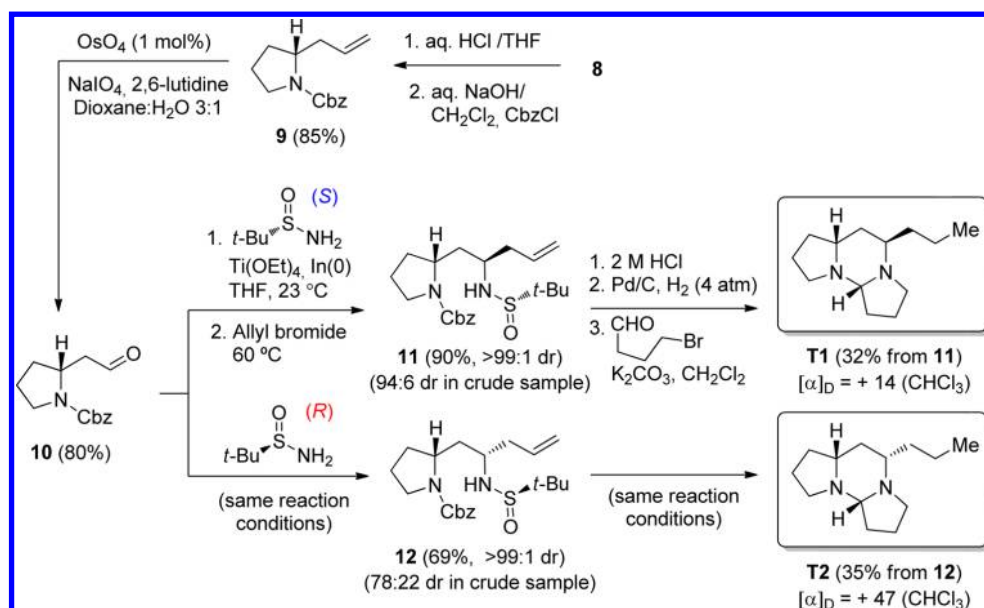


Compound **8** was a common intermediate in the synthesis of all 5–6–5 tetraponerines. Eventually, the nitrogen protecting group was exchange in a one-pot procedure by Cbz to accomplish the oxidative cleavage of the terminal double bond under modified Johnson–Lemieux conditions (Scheme 5). The obtained aldehyde **10** was submitted to a second amino-allylation reaction with (*R*)- or (*S*)-*N*-*tert*-butylsulfinamides. Gratifyingly, as occurred in the case of the 6–6–5-tetraponerines, the stereocontrol exerted by the sulfinyl group

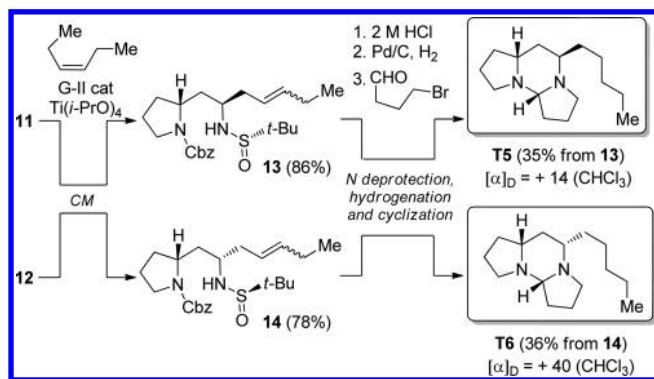
overcomes the influences of the chiral aldehyde moiety. Consequently, protected diamines **11** and **12** could be obtained in good isolated yields and excellent diastereoselectivities after column chromatography (>99:1 dr by HPLC). In this case the match-mismatched effect was stronger than with piperidine-derivative substrates, achieving a 90% yield of diastereomerically pure **11** after purification (94:6 dr before chromatography) and a 69% yield of **12** isolated as a single isomer after purification (only 78:22 dr before chromatography). Contrary to what was observed for the piperidine aldehyde **2**, in this case the matched product was obtained when (*S*)-*N*-*tert*-butylsulfinamide was used. Importantly, we were able to confirm the absolute configuration of diamine derivative **12** by single crystal X-ray analysis,²⁷ and it was found to be consistent with the stereochemistry predicted by our working model for the aminoallylation step.²⁰ Finally, the syntheses of (+)-**T1** and (+)-**T2** were completed after acidic deprotection, catalytic hydrogenation, and reaction of both free diamines with 4-bromobutanal. The GC–MS data obtained shows essentially one peak with a fragmentation pattern that perfectly matched with the one reported for **T1** and **T2**.⁹ Moreover, the ¹H and ¹³C NMR of the obtained **T2** also shows a good correlation with the data described in the literature.¹⁵ However, the NMR spectral data obtained for **T1** shows more signals than the ones described in the literature for this tetraponerine (a very minor component in the natural source).²⁸ Contrary to what has been observed for the other tetraponerines prepared, this *worst* NMR correlation could be explained if different isomers of **T1** with different configurations at C_{11a} are under equilibrium.

Finally, tetraponerines **T5** and **T6** were prepared by including in the reaction sequence the cross-metathesis step of diamine derivatives **11** of **12**, respectively, with *cis*-3-hexene (Scheme 6). After acidic treatment and catalytic hydrogenation, the obtained free diamines were treated, as in other cases, with 4-bromobutanal to obtain the corresponding tetraponerines in moderate overall yields. Once again, the GC–MS of compounds **T5** and **T6**,⁹ as well as the NMR data for **T6**,^{13b,29} were in good agreement with the literature. However, the NMR data obtained for compound **T5** showed more signals

Scheme 5. Synthesis of Tetraponerines (+)-T1** and (+)-**T2****



Scheme 6. Synthesis of Tetraoponerines (+)-T5 and (+)-T6



than the previously reported.³⁰ Since the same disagreement was found for T1 we hypothesized that these 5–6–5 tetraoponerines with (*S*)-configuration at C₅ are actually a mixture of different amina isomers in equilibrium with comparable energies. However, this hypothesis was not further confirmed.

The Bohlmann Bands in IR Spectra of Tetraoponerines.

A brief comment is in order here related to the use of the Bohlmann bands to assign the configuration at C₅ of tetraoponerines.³¹ The relevant region of the IR spectra obtained for the synthesized tetraoponerines are shown in Figure 3. The

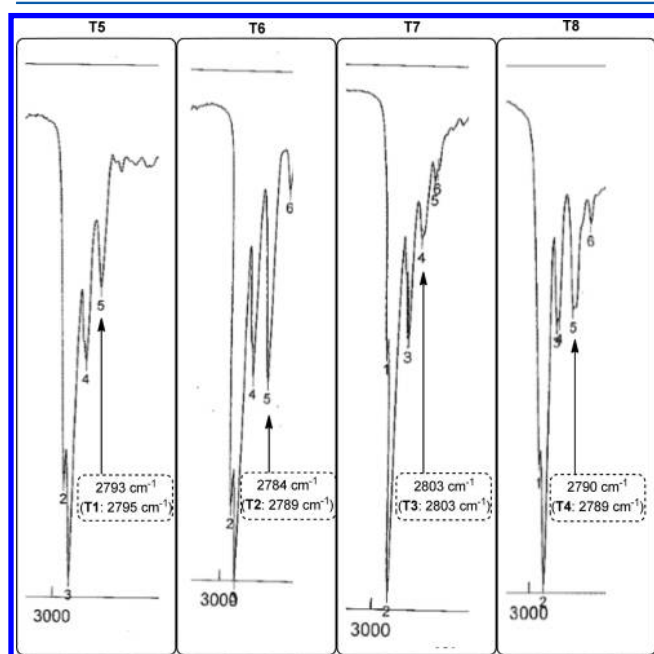


Figure 3. Bohlmann bands in the IR spectra of tetraoponerines.

presence of bands for C–H stretching at relatively low vibrational frequencies (2780–2810 cm^{−1}) can be observed for the IR spectra obtained for the synthesized tetraoponerines. The origin of these so-called Bohlmann bands is not accurately known but has been related to the lengthening of C–H_{axial} bonds because of the hyperconjugation of the adjacent nitrogen lone pair with the antiperiplanar antibonding C–H orbitals (n → σ* C–H).³²

As reported,⁹ the even-numbered tetraoponerines (T2, T4, T6, and T8) with (*S*)-configuration at C₅ show a more severe deviation on these C–H bands, which appear at lower

vibrational frequencies, and more intense compared to the odd-numbered tetraoponerines (T1, T3, T5 and T7). It is reasonable to consider that the configurational analyses performed for T3 and T4 by DFT calculations¹⁶ can be extrapolated to T7 and T8. Consequently, the even-numbered tetraoponerines (T4 and T8) must be mainly populated by a *ttt*-isomer, while the *ttc* is the major isomer for T3 and T7. As depicted in Figure 2, *ttt*-T4 and *ttt*-T8 exhibit two nitrogen atoms with electron pairs antiperiplanar to 5 C–H bonds, whereas *ttc*-isomers exhibit only one N–lone pair antiperiplanar to 3 C–H bonds. Consequently, the Bohlmann bands pattern of the 6–6–5-tetraoponerines can be rationalized in terms of the facility for hyperconjugation of nitrogen lone pairs with antiperiplanar C–H bonds. Extrapolation of this explanation to the 5–6–5-tetraoponerines is not straightforward, especially to the light of our NMR data for T1 and T5. However, the same pattern is observed for the Bohlmann bands, and their use to predict the configuration at C₅ of tetraoponerines is still valid.

Biological Assays. The biological activities of tetraoponerines have been only briefly examined, probably because of their poor availability either by isolation from their natural source or by chemical synthesis. Among the few studies accomplished, an assessment of the anticancer activity of some natural tetraoponerines and their analogues against HT-29 cell line (colorectal carcinoma), showed that the larger hydrocarbonated chain at the C₅, the lower IC₅₀ values were obtained.⁶ With this precedent we decided to evaluate the cytotoxicity of pentyl-side-chain tetraoponerines ((+)-T5 to (+)-T8) at 4 different human carcinoma cell lines from different origins (A2780 from ovary carcinoma, NCI-H460 from lung, Caco-2 from colon, and MCF-7 from breast). In order to predict the therapeutic range, we also screened these compounds over a nontumoral cell line (MRC-5, lung fibroblasts). At a first step, all the compounds were assayed at 100 μM, and for those compounds showing a decrease in cell viability higher than 50%, a concentration–response curve was assayed in order to evaluate their cytotoxic potency (IC₅₀). Unfortunately, in most of the cases the cellular growth inhibition was not enough to calculate the IC₅₀ value; nevertheless, (+)-T7 showed promising results against A2780, MCF-7 (cellular growth inhibition >50%), being more efficient against MCF-7 cancer cells. However, (+)-T7 also showed a good percentage of inhibition at MRC-5 cell lines, which could lead to nonspecific toxic effects (Table 1).

The inhibition/concentration curves were obtained for (+)-T7 against the cell lines where the cellular growth inhibition was above 50% in order to calculate the IC₅₀ values (Table 2).³³ For A2780 and MRC-5 cell lines, the obtained IC₅₀ values were above 100 μM, and solubility problems did not allow achieving the maximum inhibitory concentration. However, an acceptable value of IC₅₀ (45 ± 3 μM) was obtained against MCF-7 cancer cells.

It is worth mentioning that in previous studies it was concluded that the cytotoxicity of tetraoponerine analogues against HT29 cancer cells was independent of the configuration at C₅.⁶ In this study we have found that the antiproliferative activity of (+)-T7 is consistently bigger than that of (+)-T8 against another three different human cell lines.

CONCLUSION

In summary, the iterative use of stereoselective aminoallylation of aldehydes with chiral *N*-tert-butylsulfinamide and in situ generated allyl indium reagent provides a convenient access to all natural tetraoponerines from easily available starting materials.

Table 1. Cellular Growth Inhibition Percentage of (+)-T5, (+)-T6, (+)-T7, and (+)-T8 at 100 μ M against Human Cell Lines^a

compound	cell line				
	NCI-H460 ^b	Caco-2 ^c	A2780 ^c	MCF-7 ^c	MRC-5 ^d
CDDP	68	58	96	89	90
(+)-T5	29	20	40	49	43
(+)-T6	40	28	30	27	26
(+)-T7	48	41	62	82	55
(+)-T8	21	12	49	49	35

^aCell lines: NCI-H460, lung carcinoma; Caco-2, colon carcinoma; A2780, ovary carcinoma; MCF-7, breast carcinoma; MRC-5, human lung fibroblast cells. ^b48 h cellular growth inhibition (%) as determined by MTT. ^c96 h cellular growth inhibition (%) as determined by MTT. ^d7 d cellular growth inhibition (%) as determined by MTT. MTT = (3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazolium bromide). CDDP (*cis*-diaminedichloroplatinum(II)) was used as control.

Table 2. Assessment of Cytotoxicity (IC₅₀, μ M) of (+)-T7 against Human Cell Lines^a

compound	cell line		
	A2780 ^b	MCF-7 ^b	MRC-5 ^c
CDDP	0.86 \pm 0.01	8.18 \pm 0.56	5.72 \pm 0.14
(+)-T7	>100	45 \pm 3	>100

^aCell lines: A2780, ovary carcinoma; MCF-7, breast carcinoma; MRC-5, human lung fibroblast cells. ^bDetermined after 96 h using the MTT method. ^cDetermined after 7 d using the MTT method. MTT = (3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazolium bromide). CDDP (*cis*-diaminedichloroplatinum(II)) was used as control.

The formation of the tricyclic amina scaffold was achieved by reaction of the corresponding free enantioenriched diamines with 4-bromobutanol, with concomitant N₄ alkylation. The configuration at the amina carbon center was thermodynamically controlled with excellent selectivity in the synthesis of any natural tetraoponerine, except for (+)-T1 and (+)-T5. Interestingly, this methodology allows the access not only to the eight natural tetraoponerines, but also to their eight enantiomers, by only changing the (*R*)-*tert*-butylsulfinamide for the also commercially available (*S*)-enantiomer in the first aminoallylation step. Importantly, the cross metathesis step could be extended to the use of other alkenes, being possible the synthesis of a wide range of tetraoponerine analogues for their biological evaluation. The antiproliferative activity of (+)-T5 to (+)-T8 against four different carcinoma cell lines show that the configuration at C₅ could be important in their potency. Compound (+)-T7 showed a promising cytotoxic profile at breast carcinoma cell line MCF-7 when compared with its effect at nontumoral cell lines. With these results we think that further evaluation of tetraoponerines (+)-T7 and (+)-T8, or analogues with the same scaffold, against other cancer cell lines is pertinent in future works.

EXPERIMENTAL SECTION

General Remarks. TLC was performed on silica gel 60 F₂₅₄, using aluminum plates and visualized with phosphomolybdic acid (PMA) stain. Flash chromatography was carried out on handpacked columns of silica gel 60 (230–400 mesh). Melting points are uncorrected. Optical rotations were measured using a polarimeter with a thermally jacketed 5 cm cell at approximately 20 °C, and concentrations (*c*) are given in g/100 mL. Infrared analysis was performed with a

spectrophotometer equipped with an ATR component; wavenumbers are given in cm⁻¹. Mass spectra (EI) were obtained at 70 eV, and fragment ions in *m/z* with relative intensities (%) in parentheses. HRMS analyses were carried out using the electron impact (EI) mode at 70 eV or by Q-TOF using electrospray ionization (ESI) mode. GC analyses were obtained with an HP-5 column (30 m \times 0.25 mm, ID \times 0.25 μ m) and an EI (70 EV) detector. The temperature program was as follows: hold at 60 °C for 3 min, ramp from 60 to 270 °C at 15 °C/min, hold at 270 °C for 10 min. ¹H NMR spectra were recorded at 300 or 400 MHz for ¹H NMR and 75 or 100 MHz for ¹³C NMR, using CDCl₃ or C₆D₆ as the solvent and TMS as an internal Standard (0.00 ppm). The data is being reported as s = singlet, d = doublet, t = triplet, m = multiplet or unresolved, br s = broad signal, coupling constant(s) in Hz, integration. ¹³C NMR spectra were recorded with ¹H-decoupling at 100 MHz and referenced to CDCl₃ at 77.16 ppm and to C₆D₆ at 127.00 ppm. DEPT-135 experiments were performed to assign CH, CH₂ and CH₃.

Biological Procedures. Procedures used for biological assays are described in the Supporting Information.

Experimental Procedures and Full Characterization Data for Previously Reported Compounds. Procedure as well as complete characterization data for compounds 1,^{20a} 2, 3, 4, T3, and T4 were previously described by our group.¹⁶

(2*R*,2'*R*,5_J)-(N-Benzyloxycarbonyl)-2-[(2'-*tert*-butylsulfinamide)-4'-heptenyl]piperidine (5). The corresponding homoallylamine 3 (464 mg, 1.16 mmol) was placed in four different dry Schlenk tubes under Argon atmosphere (116 mg each).³⁴ In each flask, the homoallylamine was dissolved in dry CH₂Cl₂ (5 mL). Then Ti(Oi-Pr)₄ (27 μ L, 0.09 mmol), *cis*-3-hexene (143 μ L, 1.16 mmol), and Grubbs-II catalyst (7 mg, 0.009 mmol) were added sequentially. The reaction mixtures were heated at 40 °C for 6 h. After that time, all reactions were collected together, and the solvent was removed under reduced pressure. The residue obtained was purified by column chromatography (3:2 hexane/EtOAc). The expected product 5 was obtained as a colorless wax (391 mg, 79%). Rotamers are present: [α]_D²⁰ + 50.5 (*c* 1.01, CHCl₃); *R*_f 0.21 (1:1 hexane/EtOAc); IR ν 3242, 2935, 2867, 1677, 1421, 1352, 1260, 1173, 1142, 1064, 730 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 7.43–7.30 (m, 5H), 5.62–5.42 (m, 1H), 5.37–5.26 (m, 1H), 5.14 (t, *J* = 12.5 Hz, 2H), 4.91–4.33 (m, 2H), 4.05 (br d, *J* = 12.9 Hz, 1H), 2.91 (br s, 1H), 2.77 (t, *J* = 12.4 Hz, 1H), 2.39 (br s, 1H), 2.35–2.19 (m, 1H), 2.11–1.89 (m, 3H), 1.82–1.33 (m, 7H), 1.20 (s, 9H), 1.02–0.94 (t, *J* = 7.4 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 155.8 (C), 136.9 (C), 135.4 (CH), 128.5 (CH), 127.9 (CH), 127.8 (CH), 125.4 (CH), 67.1 (CH₂), 55.6 (C), 53.4 (CH₃), 47.6 (CH), 39.3 (CH₂), 39.2 (CH₂), 36.2 (CH₂), 29.3 (CH₂), 25.7 (CH₂), 25.6 (CH₂), 22.8 (CH), 19.2 (CH₂), 13.9 (CH₃); GC *t*_R = 20.0 min; LRMS (EI) *m/z* (%) 378 (M⁺ – C₄H₈, 0.1), 328 (3), 241 (8), 218 (31), 175 (8), 174 (58), 92 (8), 91 (100); HRMS (ESI) calcd for C₂₄H₃₉N₂O₃S (M⁺ + 1) 435.2681, found 435.2670.

(2*R*,2'*S*,5_J)-(N-Benzyloxycarbonyl)-2-[(2'-*tert*-butylsulfinamide)-4'-heptenyl]piperidine (6). The expected product 6 was obtained from 4 (337 mg, 0.83 mmol) as a colorless wax (299 mg, 83%) following the same procedure described for 5. Rotamers are present: [α]_D²⁰ – 17.6 (*c* 1.05, CHCl₃); *R*_f 0.21 (1:1 hexane/EtOAc); IR ν 3239, 2932, 2867, 1692, 1422, 1259, 1172, 1065, 1053, 697 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 7.42–7.30 (m, 5H), 5.70–5.47 (m, 1H), 5.41–5.24 (m, 1H), 5.20–5.03 (m, 2H), 4.48 (s, 1H), 4.06 (d, *J* = 12.0 Hz, 1H), 3.22 (dd, *J* = 12.4, 6.1 Hz, 1H), 2.89 (t, *J* = 13.1 Hz, 1H), 2.40 (s, 1H), 2.29 (s, 1H), 2.11–1.91 (m, 3H), 1.88–1.53 (m, 7H), 1.50–1.32 (m, 1H), 1.17 (s, 9H), 0.97 (t, *J* = 7.5 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 155.4 (C), 137.4 (C), 136.9 (CH), 128.6 (CH), 128.6 (CH), 128.0 (CH), 127.9 (CH), 67.1 (CH₂), 55.9 (C), 52.9 (CH), 47.8 (CH), 39.5 (CH₂), 39.3 (CH₂), 34.5 (CH₂), 27.9 (CH₂), 25.8 (CH₂), 25.6 (CH₂), 22.7 (CH₃), 18.9 (CH₂), 14.1 (CH₃); GC *t*_R = 19.9 min; LRMS (EI) *m/z* (%) 378 (M⁺ – C₄H₈, 0.1), 328 (3), 241 (8), 218 (31), 175 (8), 174 (58), 92 (8), 91 (100); HRMS (ESI) calcd for C₂₄H₃₉N₂O₃S (M⁺ + 1) 435.2681, found 435.2671.

Tetraoponerine T7. To a solution of compound 5 (300 mg, 0.765 mmol) in THF (2 mL) was added aqueous 6 M HCl (383 μ L, 2.30 mmol) at 0 °C under Ar. The reaction mixture was stirred for 1 h

while reaching 23 °C. Aqueous 2 M NaOH (3 mL) was added to the reaction mixture, and the free amine was extracted with EtOAc (3 × 10 mL) and washed with brine (1 × 10 mL). The organics were dried over MgSO₄, filtered, and concentrated under reduced pressure. The residue was then dissolved in dry MeOH (15 mL), and Pd/C 10% (256 mg) was added to the mixture. The suspension was shacked under hydrogen atmosphere (4 atm) for 12 h at 23 °C and filtered through Celite, and the obtained solution was concentrated under reduced pressure. The residue (free diamine) was then dissolved in dry CH₂Cl₂ (8 mL), and K₂CO₃ (317 mg, 2.30 mmol) was added, followed by 4-bromobutanal³⁵ (207 mg, 1.377 mmol). The reaction mixture was stirred at 23 °C for 4 h, after which time inorganic salts were removed by filtration. The filtrate was washed twice with aqueous NaHCO₃, followed by brine, and then dried over MgSO₄. The organics were concentrated under reduced pressure, and the residue was purified by column chromatography (96:4:0.05 CH₂Cl₂/ MeOH/ 20% NH₄OH) to provide the desired product as an oil (102 mg, 54%): $[\alpha]_D^{20} + 30$ (c 0.82, CHCl₃); [lit.^{13b} $[\alpha]_D^{20} + 29.5$ (c 2.2, CHCl₃)]; *R_f* 0.50 (9:1 CH₂Cl₂/MeOH); IR ν 2954, 2926, 2855, 2803, 1455, 1389, 1346, 1156, 1129, 1118 cm⁻¹; ¹H NMR (300 MHz, C₆D₆) δ 3.03 (dd, *J* = 4.4, 2.7 Hz, 1H), 2.90 (dd, *J* = 14.6, 7.5 Hz, 1H), 2.57–2.46 (m, 3H), 1.83–1.73 (m, 1H), 1.68 (dd, *J* = 12.5, 5.2 Hz, 1H), 1.58–1.20 (m, 9H), 1.16–0.90 (m, 10H), 0.87–0.81 (m, 1H), 0.64 (t, *J* = 6.7 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 75.5 (CH), 56.7 (CH), 53.3 (CH), 50.9 (CH₂), 50.6 (CH₂), 34.1 (CH₂), 32.5 (CH₂), 32.2 (CH₂), 31.0 (CH₂), 30.5 (CH₂), 27.3 (CH₂), 26.4 (CH₂), 25.1 (CH₂), 23.2 (CH₂), 22.2 (CH₂), 14.4 (CH₃); GC *t_R* = 13.8 min; LRMS (EI) *m/z* (%) 251 (M⁺ + 1, 6), 250 (M⁺, 44), 249 (82), 207 (19), 194 (14), 193 (100), 180 (14), 179 (10), 165 (6), 152 (34), 151 (11), 138 (10), 110 (12), 96 (30), 84 (10), 55 (6); HRMS (ESI) calcd for C₁₆H₃₁N₂ (M⁺ + 1) 251.2487, found 251.2486.

Tetraponerine T8. Tetraponerine T8 was obtained from 6 (205 mg, 0.49 mmol) as a yellow oil (74 mg, 60%) following the same procedure described for T7: $[\alpha]_D^{20} + 99$ (c 0.70, CHCl₃); [lit.^{13b} $[\alpha]_D^{20} + 101$ (c 2.0, CHCl₃)]; *R_f* 0.40 (9:1 CH₂Cl₂/MeOH); IR ν 2928, 2857, 2790, 2775, 1631, 1454, 1377, 1338, 1188, 1156, 1035 cm⁻¹; ¹H NMR (300 MHz, C₆D₆) δ 3.26 (td, *J* = 8.1, 2.2 Hz, 1H), 2.98–2.91 (m, 1H), 2.42 (t, *J* = 6.8 Hz, 1H), 2.23 (ddd, *J* = 11.0, 7.3, 3.7 Hz, 1H), 2.19–2.08 (m, 1H), 1.91–1.66 (m, 8H), 1.65–1.24 (m, 14H), 1.01 (t, *J* = 6.9 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 85.6 (CH), 62.7 (CH), 61.4 (CH), 51.5 (CH₂), 49.0 (CH₂), 38.0 (CH₂), 34.6 (CH₂), 32.9 (CH₂), 32.8 (CH₂), 29.7 (CH₂), 26.2 (CH₂), 25.2 (CH₂), 25.1 (CH₂), 23.1 (CH₂), 20.2 (CH₂), 14.3 (CH₃); GC *t_R* = 14.2 min; LRMS (EI) *m/z* (%) 251 (M⁺ + 1, 6), 250 (M⁺, 45), 249 (100), 207 (19), 194 (13), 193 (95), 180 (20), 179 (11), 165 (12), 152 (45), 151 (15), 138 (12), 137 (10), 110 (14), 96 (30), 84 (16), 55 (9); HRMS (ESI) calcd for C₁₆H₃₁N₂ (M⁺ + 1) 251.2487, found 251.2493.

(4*R*,*R*₂)-*N*-(*tert*-Butylsulfinyl)-7-bromohept-1-en-4-amine (7). To a dry flask were added (*R_S*)-*N*-*tert*-butylsulfonamide (829 mg, 6.79 mmol) followed by indium powder (968 g, 8.489 mmol) under Ar. Then a solution of 4-bromobutyraldehyde (1.121 g, 7.470 mmol) in dry THF (15.9 mL) and Ti(OEt)₄ (3.1 mL, 13.582 mmol) were added successively, and the reaction mixture was stirred under Ar for 1 h at 23 °C. At this time allyl bromide (897 μ L, 10.186 mmol) was added to the mixture, and the reaction was allowed to reach 60 °C and stirred at that temperature for 5 h. The mixture was allowed to reach room temperature and was carefully added over a stirring mixture of 4:1 EtOAc/brine (100 mL). The resulted white suspension was filtered through a short pad of Celite, washed with EtOAc, and organics were concentrated in vacuo. The resulted suspension was diluted in 4:1 EtOAc/hexane (50 mL) and filtered again through Celite. Organics were concentrated to afford the expected compound 7 (1.783 g, 89%, 95:5 dr according to ¹H NMR) as a colorless wax, pure enough to be used in the next step. To provide the spectroscopy data, a sample of homoallylamine 7 was purified by column chromatography: *R_f* 0.13 (7:3 hexane/EtOAc); ¹H NMR (300 MHz, CDCl₃) δ 5.79 (ddt, *J* = 19.6, 9.4, 7.2 Hz, 1H), 5.20 (d, *J* = 0.7 Hz, 1H), 5.16 (d, *J* = 3.6 Hz, 1H), 3.41 (t, *J* = 6.6 Hz, 3H), 3.27 (d, *J* = 6.2 Hz, 1H), 2.55–2.25 (m, 2H), 2.03–1.82 (m, 2H), 1.82–1.56 (m, 2H), 1.22 (s, 9H); ¹³C NMR

(101 MHz, CDCl₃) δ 133.8 (CH), 119.5 (CH₂), 56.2 (C), 54.5 (CH), 40.7 (CH₂), 33.7 (CH₂), 33.6 (CH₂), 29.0 (CH₂), 22.8 (CH₃); GC *t_R* = 14.1 min; LRMS (EI) *m/z* (%) 200 (40), 199 (100), 198 (39), 197 (95), 118 (15), 91 (13), 70 (80), 68 (16), 57 (66).

(2*R*,*R*₂)-2-Allyl-(*N*-*tert*-butylsulfinyl)pyrrolidine (8). A titrated solution of KHMDS in THF (7.9 mL, 1.03 M, 8.136 mmol) was added via syringe to a cold solution (0 °C) of crude 7 (1.600 g, 5.424 mmol) in dry THF (13.8 mL). The reaction mixture was stirred for 1.5 h at 0 °C under Ar, quenched with saturated NH₄Cl solution, and allowed to reach room temperature. The aqueous phase was extracted with EtOAc (3 times), and the combined extracts were washed with brine, dried over MgSO₄, and concentrated under reduced pressure. The residue was purified by column chromatography (80:20 hexane/EtOAc) to provide the product as a colorless oil (1.008 g, 86%, 97:3 dr according to the ¹H NMR): $[\alpha]_D^{20} - 17.1$ (c 1.038, CHCl₃); *R_f* 0.30 (7:3 hexane/EtOAc); IR ν 3076, 2658, 2871, 1639, 1474, 1456, 1361, 1065, 994, 911 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 5.82–5.66 (m, 1H), 5.11–5.01 (m, 2H), 3.74 (ddd, *J* = 10.1, 6.6, 3.7 Hz, 1H), 3.51–3.43 (m, 1H), 3.14 (dt, *J* = 10.7, 7.0 Hz, 1H), 2.52–2.43 (m, 1H), 2.17 (ddd, *J* = 14.0, 9.4, 8.2 Hz, 1H), 1.87–1.73 (m, 3H), 1.71–1.60 (m, 1H), 1.19 (s, 9H); ¹³C NMR (101 MHz, CDCl₃) δ 135.3 (CH), 117.3 (CH₂), 58.1 (C), 57.5 (CH), 48.6 (CH₂), 39.0 (CH₂), 30.4 (CH₂), 24.2 (CH₂), 23.7 (CH₃); GC *t_R* = 11.9 min; LRMS (EI) *m/z* (%) 215 (M⁺, 0.1), 159 (16), 118 (100), 117 (29), 70 (10), 57 (13); HRMS (EI) calcd for C₁₁H₂₁NOS 215.1344, found 215.1348.

(*R*)-2-Allyl-(*N*-benzyloxycarbonyl)pyrrolidine (9). An aqueous 6 M solution of HCl (2 mL, 12.00 mmol) was added to a solution of 8 (860 mg, 4.0 mmol) in dry THF (4 mL) at 0 °C under Ar. The solution was allowed to reach 23 °C and was stirred for 2 h. After being cooled again to 0 °C, an aqueous 2 M solution of NaOH (14 mL, 27.00 mmol) was carefully added, and the resulting mixture was stirred at the same temperature. After 5 min, a solution of benzyloxycarbonyl chloride (670 μ L, 4.70 mmol) in CH₂Cl₂ (12 mL) was added to the stirring solution. The resulting mixture was then allowed to reach 23 °C and stirred for 3 h. The reaction mixture was extracted with EtOAc (3 times), and the combined organic layers were washed with H₂O, dried over MgSO₄, filtered, and concentrated under reduced pressure. The residue was purified by column chromatography (95:5 hexane/EtOAc) to provide the desired product 9 as a colorless oil (831 mg, 85%). Rotamers are present: $[\alpha]_D^{20} + 53.1$ (c 0.617, CHCl₃); *R_f* 0.60 (7:3 hexane/EtOAc); IR ν 3035, 2972, 2876, 1696, 1639, 1446, 1407, 1355, 1100 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 7.41–7.27 (m, 5H), 5.83–5.64 (m, 1H), 5.21–4.96 (m, 4H), 3.92 (br s, 1H), 3.52–3.35 (m, 2H), 2.51 (br d, *J* = 54.4 Hz, 1H), 2.15 (td, *J* = 14.8, 8.1 Hz, 1H), 1.96–1.70 (m, 4H); ¹³C NMR (101 MHz, CDCl₃) δ 155.1 (C), 154.9 (C), 137.3 (C), 137.1 (C), 135.2 (CH), 135.0 (CH), 128.6 (CH), 127.9 (CH), 117.4 (CH₂), 66.8 (CH₂), 66.6 (CH₂), 57.4 (CH), 56.9 (CH), 47.0 (CH₂), 46.7 (CH₂), 39.1 (CH₂), 38.2 (CH₂), 30.2 (CH₂), 29.3 (CH₂), 23.8 (CH₂), 23.0 (CH₂); GC *t_R* = 14.6 min; LRMS (EI) *m/z* (%) 245 (M⁺, 0.1), 204 (26), 160 (28), 91 (100); HRMS (EI) calcd for C₁₅H₁₉NO₂ 245.1416, found 245.1427.

(*R*)-(*N*-Benzyloxycarbonyl)-2-(2-oxoethyl)pyrrolidine (10). To a solution of 9 (790 mg, 3.224 mmol) in 1,4-dioxane:H₂O (3:1, 30 mL) were successively added 2,6-lutidine (751 μ L, 6.45 mmol), NaIO₄ (2.8 g, 12.90 mmol) and a solution of OsO₄ in *t*-BuOH (2.5% wt in *t*-BuOH, 317 μ L). The mixture was stirred at 23 °C for 1.5 h before being quenched with water (20 mL). The mixture was extracted with EtOAc (3 × 10 mL), and the collected organic layers were washed with H₂O, dried over MgSO₄, filtered, and concentrated under reduced pressure. The residue was purified by column chromatography (4:1 hexane/EtOAc) to provide the pure product as a colorless oil (639 mg, 80%). Rotamers are present: $[\alpha]_D^{20} + 40.4$ (c 1.44, CHCl₃); *R_f* 0.24 (7:3 hexane/EtOAc); IR ν 3031, 2956, 2879, 2726, 1718, 1692, 1497, 1448, 1409, 1356, 1100 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 9.80 (br s, 0.6H), 9.67 (br s, 0.4H), 7.44–7.29 (m, 5H), 5.24–5.01 (m, 2H), 4.32 (dt, *J* = 12.1, 5.9 Hz, 1H), 3.58–3.27 (m, 2H), 2.99 (dd, *J* = 16.5, 3.1 Hz, 0.6H), 2.83 (br d, *J* = 16.8 Hz, 0.4H), 2.53 (d, *J* = 7.6 Hz, 0.6H), 2.48 (d, *J* = 7.6 Hz, 0.4H), 2.14 (dq, *J* = 12.5, 7.9 Hz, 1H), 1.92–1.81 (m, 2H), 1.74–1.61 (m, 1H); ¹³C NMR (101 MHz,

CDCl_3) δ 200.9 (CH), 200.6 (CH), 155.0 (C), 154.7 (C), 136.9 (C), 136.6 (C), 128.6 (CH), 128.3 (CH), 128.1 (CH), 128.0 (CH), 67.1 (CH₂), 66.9 (CH₂), 53.1 (CH), 52.3 (CH), 49.4 (CH₂), 48.7 (CH₂), 46.9 (CH₂), 46.5 (CH₂), 32.1 (CH₂), 31.3 (CH₂), 23.9 (CH₂), 23.1 (CH₂); GC t_R = 15.4 min; LRMS (EI) m/z (%) 247 (M^+ , 0.6), 219 (10), 160 (10), 156 (10), 112 (10), 91 (100), 65 (10); HRMS (EI) calcd for $\text{C}_{14}\text{H}_{17}\text{NO}_3$ 247.1208, found 247.1213.

(2*R*,2'*R*,*S*₅)-(N-Benzoyloxycarbonyl)-2-[(2'-*tert*-butylsulfinamine)-4'-pentenyl]pyrrolidine (**11**). To a dry flask were added (*S*₅)-*N*-*tert*-butylsulfinamide (134 mg, 1.107 mmol) and indium powder (158 mg, 1.38 mmol) under Ar. Then was added a solution of aldehyde **10** (301 mg, 1.218 mmol) in dry THF (2.7 mL) followed by $\text{Ti}(\text{OEt})_4$ (500 μL , 2.22 mmol), and the reaction mixture was stirred under Ar for 1 h at 23 °C. At this time allyl bromide (143 μL , 1.66 mmol) was added to the mixture, and it was heated to 60 °C for 5 h. The mixture was allowed to reach 23 °C and was carefully added over a stirring mixture of 4:1 EtOAc/brine (15 mL). The resulted white suspension was filtered through a short pad of Celite and washed with EtOAc, and the organics were concentrated under reduced pressure. According to HPLC analysis (Chiralcel AD-H column 25 cm \times 0.46 cm, isocratic elution with 95:5 *n*-hexane/*i*-PrOH, 1.0 mL/min, UV detection at 217 nm), the crude reaction mixture showed a major diastereoisomer at 16.17 min (94%) and other diastereoisomers at 20.80–23.50 min (6%). After column chromatography (3:2 hexane/EtOAc), the major isomer was isolated pure (>99:1 dr according to HPLC) as a colorless wax product as a unique diastereoisomer after purification by column chromatography (391 mg, 90%). Rotamers are present: $[\alpha]_D^{20}$ + 83.2 (*c* 1.220, CHCl_3); R_f 0.20 (1:1 hexane/EtOAc); IR ν 3243, 3065, 2957, 2888, 1685, 1452, 1409, 1360, 1099, 1062 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.44–7.28 (m, 5H), 5.80 (dq, J = 10.0, 6.9 Hz, 0.8H), 5.62 (dd, J = 15.8, 8.3 Hz, 0.2H), 5.27–5.00 (m, 5H), 4.34 (dd, J = 13.0, 7.6 Hz, 0.8H), 3.99 (br s, 0.2H), 3.42 (dt, J = 11.4, 8.5 Hz, 2H), 3.20 (qd, J = 10.1, 5.5 Hz, 1H), 2.52 (dt, J = 14.5, 7.4 Hz, 1H), 2.42–2.27 (m, 1H), 2.09–1.81 (m, 3H), 1.81–1.54 (m, 3H), 1.24 (s, 7H), 1.12 (s, 2H); ^{13}C NMR (101 MHz, CDCl_3) δ 156.3 (C), 137.0 (C), 135.6 (CH), 134.1 (CH), 128.6 (CH), 128.0 (CH), 127.8 (CH), 119.0 (CH₂), 117.5 (CH₂), 67.3 (CH₂), 66.9 (CH₂), 55.6 (C), 54.9 (CH), 53.3 (CH), 46.6 (CH₂), 42.4 (CH₂), 41.3 (CH₂), 39.8 (CH₂), 39.2 (CH₂), 31.4 (CH₂), 23.8 (CH₂), 23.0 (CH₃), 22.7 (CH₃); GC t_R = 22.7 min; LRMS (EI) m/z (%) 336 (M^+ , 0.8), 287 (6), 218 (14), 204 (10), 174 (10), 160 (20), 114 (6), 91 (100), 70 (23); HRMS (EI) calcd for $\text{C}_{21}\text{H}_{32}\text{N}_2\text{O}_3\text{S}$ – C_4H_8 336.1508, found 336.1510.

(2*R*,2'*S*,*R*₅)-(N-Benzoyloxycarbonyl)-2-[(2'-*tert*-butylsulfinamine)-4'-pentenyl]pyrrolidine (**12**). Compound **12** was prepared from aldehyde **10** (301 mg, 1.218 mmol) and (*R*₅)-*N*-*tert*-butylsulfinamide (134 mg, 1.107 mmol) following the same procedure described above for compound **11**. According to HPLC analysis (Chiralcel AD-H column 25 cm \times 0.46 cm, isocratic elution with 95:5 *n*-hexane/*i*-PrOH, 1.0 mL/min, UV detection at 217 nm), the crude reaction mixture showed a major diastereoisomer at 21.4 min (78%) and other diastereoisomers at 14.4–17.0 min (22%). After column chromatography (3:2 hexane/EtOAc), the major isomer was isolated pure (>99:1 dr according to HPLC) as a colorless wax (301 mg, 69%): mp 76.5–77.1 °C; $[\alpha]_D^{20}$ –31.8 (*c* 0.929, CHCl_3); R_f 0.16 (1:1 hexane/EtOAc); IR ν 3203, 3075, 2958, 2883, 1689, 1471, 1453, 1407, 1096, 1045, 1032 cm^{-1} ; Rotamers are present (as shown in the X-ray at the Supporting Information) ^1H NMR (300 MHz, CDCl_3) δ 7.48–7.32 (m, 5H), 5.94–5.58 (m, 1H), 5.27–4.94 (m, 4H), 4.04 (br d, J = 35.6 Hz, 1H), 3.58–3.36 (m, 2.6H), 3.28 (br d, J = 32.9 Hz, 1H), 3.02 (d, J = 8.4 Hz, 0.4H), 2.58–2.31 (m, 2H), 2.09–1.80 (m, 4H), 1.68 (br d, J = 5.1 Hz, 1H), 1.51–1.35 (m, 1H), 1.22 (s, 5H), 1.06 (s, 4H); ^{13}C NMR (101 MHz, CDCl_3) δ 154.9 (C), 137.1 (C), 137.0 (C), 134.0 (CH), 133.3 (CH), 128.7 (CH), 128.6 (CH), 128.4 (CH), 128.0 (CH), 127.9 (CH), 119.8 (CH₂), 119.2 (CH₂), 67.2 (CH₂), 66.6 (CH₂), 56.4 (C), 56.2 (C), 55.2 (CH), 54.6 (CH), 54.5 (CH), 54.3 (CH), 46.7 (CH₂), 46.4 (CH₂), 42.2 (CH₂), 42.0 (CH₂), 40.3 (CH₂), 39.5 (CH₂), 30.5 (CH₂), 30.1 (CH₂), 23.9 (CH₂), 23.1 (CH₂), 22.9 (CH₃), 22.7 (CH₃); GC t_R = 22.9 min; LRMS (EI) m/z (%) 336 (M^+ , 0.8), 287 (6), 218 (14), 204 (10), 174 (10), 160 (25), 114 (12), 91

(100), 70 (23); HRMS (EI) calcd for $\text{C}_{21}\text{H}_{32}\text{N}_2\text{O}_3\text{S}$ – C_4H_8 336.1508, found 336.1509.

Tetraponerine T1. Tetraponerine **T1** was prepared from **11** (300 mg, 0.765 mmol) and 4-bromobutanol (207 mg, 1.377 mmol) following the same procedure described above for compound **T7**, affording the expected product as an oil (51 mg, 32% from **11**). Configurational isomers must be present: $[\alpha]_D^{20}$ + 14 (*c* 0.498, CHCl_3) [lit.¹⁵ $[\alpha]_D^{20}$ + 11 (*c* 0.14, CHCl_3)]; R_f 0.15 (95:5 $\text{CH}_2\text{Cl}_2/\text{MeOH}$); IR ν 2954, 2928, 2871, 2792, 2639, 2585, 1457, 1381, 1349, 1191, 1167, 1111 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 3.92–3.74 (m, 1H), 3.46–3.15 (m, 2H), 3.14–2.88 (m, 2H), 2.77–2.36 (m, 1H), 2.31–1.78 (m, 8H), 1.79–1.16 (m, 7H), 0.92 (t, J = 7.3 Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ 77.0 (CH), 58.4 (CH), 53.7 (CH), 50.4 (CH₂), 49.8 (CH₂), 33.8 (CH₂), 30.8 (CH₂), 29.5 (CH₂), 29.2 (CH₂), 21.3 (CH₂), 20.5 (CH₂), 20.1 (CH₂), 14.3 (CH₃); GC t_R = 11.6 min; LRMS (EI) m/z (%) 208 (M^+ , 46), 207 (100), 180 (12), 179 (91), 165 (10), 138 (51), 137 (19), 124 (23), 110 (17), 96 (64), 70 (29); HRMS (EI) calcd for $\text{C}_{13}\text{H}_{24}\text{N}_2$ 208.1939, found 208.1929.

Tetraponerine T2. Tetraponerine **T2** was prepared from **12** (230 mg, 0.587 mmol), and 4-bromobutanol (159 mg, 1.057 mmol) following the same procedure described above for compound **T7**, affording the expected product as an oil (42 mg, 35% from **12**): $[\alpha]_D^{20}$ + 47 (*c* 0.232, CHCl_3) [lit.¹⁵ $[\alpha]_D^{20}$ + 36 (*c* 1.79, CHCl_3)]; R_f 0.15 (95:5 $\text{CH}_2\text{Cl}_2/\text{MeOH}$); IR ν 2955, 2931, 2871, 2787, 2695, 1457, 1379, 1362, 1190, 1162, 1099 cm^{-1} ; ^1H NMR (300 MHz, C_6D_6) δ 3.17–2.93 (m, 3H), 2.60–2.51 (m, 1H), 2.43 (td, J = 8.7, 5.1 Hz, 1H), 2.07–1.83 (m, 5H), 1.83–1.60 (m, 4H), 1.60–1.25 (m, 7H), 1.01 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, C_6D_6) δ 83.0 (CH), 63.8 (CH), 59.1 (CH), 48.6 (CH₂), 45.5 (CH₂), 36.5 (CH₂), 32.7 (CH₂), 30.4 (CH₂), 28.9 (CH₂), 21.1 (CH₂), 20.8 (CH₂), 19.3 (CH₂), 14.6 (CH₃); GC t_R = 11.9 min; LRMS (EI) m/z (%) 208 (M^+ , 41), 207 (100), 180 (8), 179 (53), 165 (11), 138 (59), 137 (20), 124 (25), 110 (18), 96 (47), 70 (37); HRMS (EI) calcd for $\text{C}_{13}\text{H}_{24}\text{N}_2$ 208.1939, found 208.1932.

(2*R*,2'*R*,*S*₅)-(N-Benzoyloxycarbonyl)-2-[(2'-*tert*-butylsulfinamine)-4'-heptenyl]pyrrolidine (**13**). Compound **13** was prepared from **11** (513 mg, 1.31 mmol) following the same procedure described above for compound **5**, affording the corresponding product as a colorless wax (473 mg, 86%). Rotamers are present: $[\alpha]_D^{20}$ + 81.6 (*c* 1.20, CHCl_3); R_f 0.31 (1:1 hexane/EtOAc); IR ν 3248, 3031, 2958, 2931, 1685, 1453, 1409, 1359, 1099, 1062, 968, 697 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.46–7.31 (m, 5H), 5.66–5.48 (m, 1H), 5.47–5.29 (m, 1H), 5.29–5.03 (m, 2H), 4.42–3.89 (m, 1H), 3.56–3.05 (m, 3H), 2.42 (dt, J = 14.1, 7.1 Hz, 1H), 2.34–2.19 (m, 1H), 1.23 (s, 7H), 1.12 (s, 2H), 1.18 (d, J = 34.3 Hz, 9H), 0.96 (t, J = 7.4 Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ 156.1 (C), 137.0 (C), 135.4 (CH), 128.6 (CH), 128.0 (CH), 127.8 (CH), 125.6 (CH), 66.9 (CH₂), 55.7 (C), 55.0 (CH), 53.5 (CH), 46.5 (CH₂), 42.2 (CH₂), 38.0 (CH₂), 31.3 (CH₂), 25.8 (CH₂), 23.8 (CH₂), 22.9 (CH₃), 22.7 (CH₃), 14.3 (CH₃), 13.9 (CH₃); GC t_R = 19.4 min; LRMS (EI) m/z (%) 314 (3), 227 (3), 204 (12), 173 (4), 161 (3), 160 (23), 145 (24), 92 (8), 91 (100), 70 (6), 69 (3), 65 (5); HRMS (ESI) calcd for $\text{C}_{23}\text{H}_{37}\text{N}_2\text{O}_3\text{S}$ (M^+ + 1) 421.2525, found 421.2521.

(2*R*,2'*S*,*R*₅)-(N-Benzoyloxycarbonyl)-2-[(2'-*tert*-butylsulfinamine)-4'-heptenyl]pyrrolidine (**14**). Compound **14** was prepared from **12** (358 mg, 0.90 mmol) following the same procedure described above for compound **5**, affording the corresponding product as a colorless wax (295 mg, 78%). Rotamers are present: $[\alpha]_D^{20}$ – 20.5 (*c* 0.99, CHCl_3); R_f 0.30 (1:1 hexane/EtOAc); IR ν 3232, 3030, 2959, 2873, 1691, 1454, 1412, 1359, 1102, 1057, 970, 750 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 7.41–7.30 (m, 5H), 5.59 (dt, J = 15.2, 6.4 Hz, 1H), 5.47–5.22 (m, 1H), 5.22–4.97 (m, 2H), 4.18–3.87 (m, 1H), 3.59–3.00 (m, 4H), 2.34 (br d, J = 21.0 Hz, 2H), 2.11–1.92 (m, 4H), 1.92–1.59 (m, 3H), 1.37 (dd, J = 24.1, 12.3 Hz, 1H), 1.23 (s, 5H), 1.05 (s, 4H), 0.97 (t, J = 7.5 Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ 154.7 (C), 137.7 (CH), 137.2 (CH), 136.9 (C), 136.8 (C), 128.4 (CH), 128.2 (CH), 127.9 (CH), 127.7 (CH), 123.8 (CH), 123.1 (CH), 67.0 (CH₂), 66.5 (CH₂), 56.1 (C), 55.9 (C), 55.1 (CH), 54.6 (CH), 54.4 (CH), 46.6 (CH₂), 46.2 (CH₂), 40.6 (CH₂), 40.5 (CH₂), 40.2 (CH₂), 39.3 (CH₂), 30.4 (CH₂), 29.9 (CH₂), 25.7 (CH₂), 23.7 (CH₂), 22.8

(CH₃), 22.5 (CH₃), 20.7 (CH₂), 14.2 (CH₃), 13.9 (CH₃); GC t_R = 19.4 min; LRMS (EI) m/z (%) 314 (3), 227 (3), 207 (3), 204 (11), 179 (3), 174 (4), 173 (4), 161 (3), 160 (23), 145 (9), 92 (8), 91 (100), 70 (6), 65 (4); HRMS (ESI) calcd for C₂₃H₃₇N₂O₃S (M⁺ + 1) 421.2525, found 421.2519.

Tetraponerine T5. Tetraponerine T5 was prepared from 13 (460 mg, 1.10 mmol), and 4-bromobutanol following the same procedure described above for compound T7, affording the expected product as a yellow oil (90 mg, 35%). Configurational isomers must be present: $[\alpha]_D^{20} + 14$ (c 1.60, CHCl₃), [lit.¹⁵ $[\alpha]_D^{20} + 10$ (c 0.24, CHCl₃)]; R_f 0.35 (9:1 CH₂Cl₂/MeOH); IR ν 3414, 2953, 2927, 2857, 2793, 1457, 1384, 1348, 1233, 1162, 1114, 1064 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 3.75–3.45 (m, 1H), 3.40–2.64 (m, 4H), 2.62–2.15 (m, 1H), 2.16–1.43 (m, 12H), 1.40–0.98 (m, 7H), 0.89 (dd, J = 9.0, 4.3 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 59.9 (CH), 58.3 (CH), 53.9 (CH), 50.3 (CH₂), 49.5 (CH₂), 31.9 (CH₂), 31.3 (CH₂), 30.6 (CH₂), 29.3 (CH₂), 29.0 (CH₂), 26.9 (CH₂), 22.6 (CH₂), 21.1 (CH₂), 20.0 (CH₂), 14.1 (CH₃); GC t_R = 13.0 min; LRMS (EI) m/z (%) 237 (5), 236 (M⁺, 42), 235 (100), 193 (13), 180 (12), 179 (81), 166 (15), 165 (6), 152 (11), 138 (27), 137 (12), 124 (10), 110 (21), 96 (43), 70 (18), 55 (7); HRMS (ESI) calcd for C₁₅H₂₉N₂ (M⁺ + 1) 237.2331, found 237.2324.

Tetraponerine T6. Tetraponerine T6 was prepared from 14 (255 mg, 0.61 mmol), and 4-bromobutanol following the same procedure described above for compound T7, affording the expected product as a yellow oil (52 g, 36%): $[\alpha]_D^{20} + 40$ (c 0.75, CHCl₃), [lit.¹⁵ $[\alpha]_D^{20} + 35$ (c 0.31, CHCl₃)]; R_f 0.50 (9:1 CH₂Cl₂/MeOH); IR ν 3395, 2954, 2928, 2858, 2784, 1458, 1378, 1204, 1188, 1161, 1064 cm⁻¹; ¹H NMR (300 MHz, C₆D₆) δ 3.11–3.01 (m, 1H), 2.94 (td, J = 8.4, 2.5 Hz, 1H), 2.85 (t, J = 5.3 Hz, 1H), 2.48–2.36 (m, 1H), 2.32 (dd, J = 8.4, 5.3 Hz, 1H), 2.00–1.84 (m, 2H), 1.83–1.52 (m, 7H), 1.50–1.19 (m, 11H), 0.91 (t, J = 6.9 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 83.4 (CH), 64.2 (CH), 59.7 (CH), 49.1 (CH₂), 45.9 (CH₂), 34.7 (CH₂), 33.5 (CH₂), 32.6 (CH₂), 30.6 (CH₂), 29.2 (CH₂), 25.9 (CH₂), 23.1 (CH₂), 21.3 (CH₂), 20.9 (CH₂), 14.4 (CH₃); GC t_R = 13.3 min; LRMS (EI) m/z (%) 237 (M + 1, 5), 236 (M⁺, 40), 235 (100), 207 (5), 193 (15), 180 (8), 179 (54), 166 (17), 165 (10), 152 (13), 151 (10), 138 (38), 137 (14), 124 (12), 123 (5), 110 (14), 97 (7), 96 (35), 70 (24), 68 (7), 55 (6); HRMS (ESI) calcd for C₁₅H₂₉N₂ (M⁺ + 1) 237.2331, found 237.2333.

■ ASSOCIATED CONTENT

Supporting Information

Copies of ¹H and ¹³C NMR spectra for compounds 5–14, T1, T2, and T5–T8 are provided. GC–MS for T1–T8, HPLC traces of compounds 11 and 12, crystallographic data (CIF) for compound 12, as well as cytotoxic data for T5–T8 against four different carcinoma cell lines are also included. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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(35) 4-Bromobutanal is commercially available, but we prepared it by DIBAL-H reduction of the corresponding methyl ester.

(36) To ensure that the amine was not partially protonated, the sample was washed with saturated solution of NaHCO₃ before submitting to NMR experiments. Similar NMR spectra were obtained in CDCl₃ and CD₂Cl₂ (where traces of HCl are less likely).