HETEROCYCLES, Vol. 60, No. 8, 2003, pp. 1833 - 1841
Received,6th May, 2003, Accepted,20th June, 2003, Published online, 23rd June, 2003

SYNTHESIS OF (*S*)-VASICOL AND (*S*)-3-HYDROXY-2-PYRROLIDINONE

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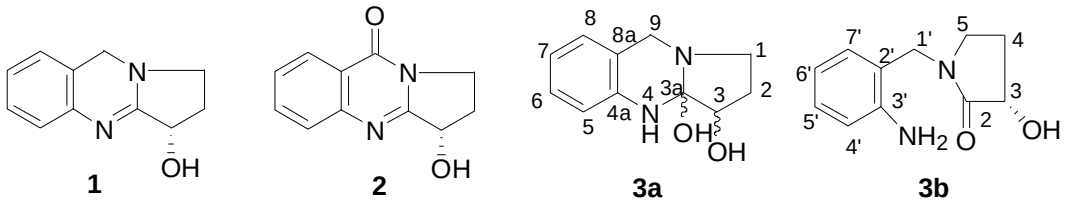
Abstract – Starting from (*S*)-malic acid, a flexible approach to (*S*)-3-hydroxy-2-pyrrolidinone and (*S*)-1-alkyl-3-hydroxy-2-pyrrolidinones was reported. Using this method, the first total syntheses of (-)-vasicol as well as deaminovasicol were accomplished, which allowed the revision and clarification the confusion about the structure of naturally occurring (-)-vasicol.

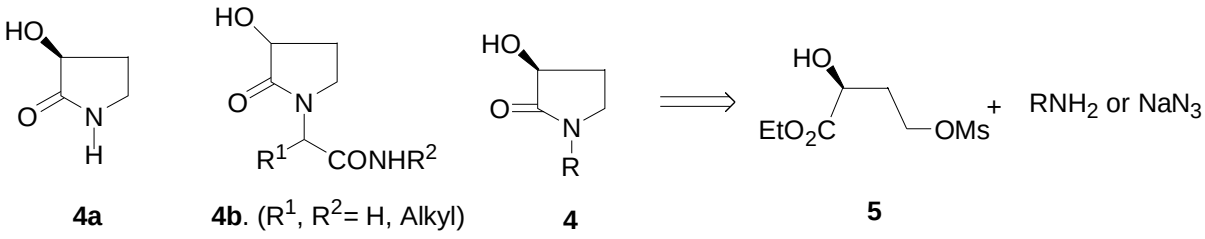
INTRODUCTION

Adhatoda vasica Nees is a well-known plant drug in Ayurvedic and Unani medicine. It has been used for the treatment of various diseases and disorders, particularly for the respiratory tract ailments.[1] The plant is a rich source of the quinazoline alkaloids,[2] from which the isolations of (-)-vasicine (**1**) (peganine), (+)-vasicinol (7-hydroxyvasicine), 5-methoxyvasicine, (-)-vasicinone (**2**), (±)-vasicinone, (7-hydroxy-vasicinone), 5-methoxyvasicinone, 5-methoxyvasicinone, (-)-vasicol (**3**), vasicoline, and vasicolinone have been reported. Although structurally simple, both the absolute configuration of these alkaloids and the structure of vasicol (**3**) are confusable. The traditional assigned[3] (3*R*)-configuration for (-)-vasicine (**1**) (and related alkaloids) [4] on the basis of an X-Ray analysis of its hydrochloride has been reversed by reinvestigation of the X-Ray diffraction analysis of the hydrobromide[5a] and by using the Mosher ester analysis method, [5b] which was finally confirmed by the asymmetric synthesis of both enantiomers of vasicinone (**2**).[6] On the other hand, there is confusion on the structure of vasicol. (-)-Vasicol, in the form of 1,2,3,4,9,11-hexahydropyrrolo[2,1-*b*]quinazoline-3,11-diol (**3a**), was originally obtained from the roots of plant *Adhatoda vasica* Nees and also by hydration of vasicine (peganine, **1**).[7] However, on the basis of an X-Ray diffraction analysis of 4-bromovasicol, Russian chemists assigned 2-(3'-hydroxy-2'-oxopyrrolidinomethyl)aniline (**3b**) to vasicol, obtained from *Peganum harmala* and by hydration of peganine (vasicine **1**).[8] More recently, Joshi and co-workers[9] reported on the detailed ^{1}H- and ^{13}C-NMR spectral assignments of (-)-vasicol (**3a**), obtained from the leaves of *Adhatoda vasica*. Curiously, in later

report, neither Russian chemists' important results nor the possibility for **3a** to exist in another tautomer (**3b**) has been mentioned.



In order to clarify the structure of vasicol (**3a**/**3b**), and in connection with a related synthetic program,[10] we envisioned a synthetic route to (*S*)-3-hydroxy-2-pyrrolidinones of general structure (**4**) (**Scheme 1**). Hydroxy-2-pyrrolidinone (**4a**) is a useful chiral building block, its *O*-silyl derivative has been used in the first synthesis of (-)-vasicinone (**2**).[6] Moreover, **4a** is a structural unity found in pharmaceutically interesting molecules and bioactive natural products. For example, compounds of general structure (**4b**) are of interest for treatment of brain insufficiencies and as cognition activators.[11]



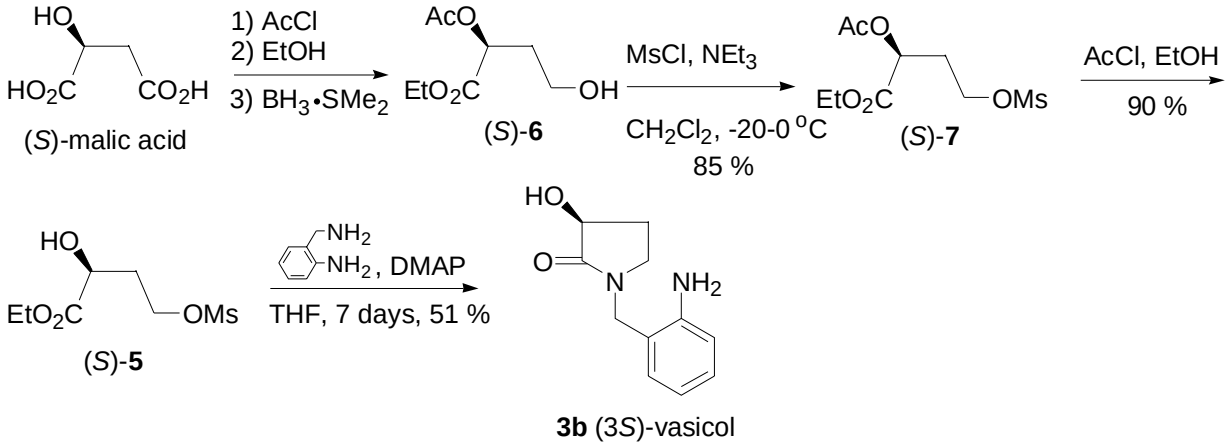
Scheme 1

RESULTS AND DISCUSSION

Our synthesis started from cheap and easily available (*S*)-malic acid. Thus, as outlined in Scheme 2, (*S*)-malic acid was transformed into known compound (*S*-**6)** by a known three-step procedure,[12] namely, (*S*)-malic acid anhydride formation-regioselective ethanolysis and chemoselective carboxylic acid reduction. In this way, (*S*)-**6** was obtained in an overall yield of 75 % from (*S*)-malic acid.

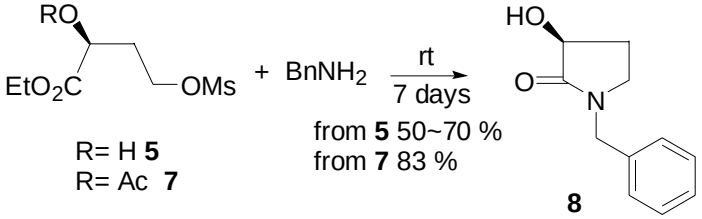
Mesylation (MsCl, NEt_3, CH_2Cl_2, -20-0 °C) of (*S*)-**6** afforded (*S*)-**7** in 85% yield. Acetate (**7**) was then subjected to selective ethanolysis conditions (AcCl, EtOH, room temperature), which provided the desired (*S*)-**5** in high yield (90%). Treatment of (*S*)-**5** with two molar equivalents of *O*-aminobenzylamine in THF at room temperature for one day, followed by the addition of one molar equivalent of 4-dimethylaminopyridine and allowed to react for another six days afforded the desired (*S*)-vasicol {**3b**, pale yellow oil. $[\alpha]^{20}_D$ –90.4° (*c* 0.95, $CHCl_3$)}in 51 % yield. The structural assignment was made based

on both the characteristic amide carbonyl IR absorption at 1674 cm^{-1} and the amide carbonyl ^{13}C-NMR shift appeared at 175.1 ppm.



Scheme 2

Since **3a** and **3b** are tautomers, in order to further confirm the structure of our synthetic vasicol (**3b**), the synthesis of deaminovasicol (**8**) was preceded (**Scheme 3**). Thus the reaction of (*S*)-**5** with benzylamine under the conditions described for vasicol provided deaminovasicol (*S*-**8**) in 50-70 % yields. Higher yield (83 %) of (*S*)-**8** was obtained by direct reaction of (*S*)-**7** with three molar equivalents of benzylamine. 2-Pyrrolidinone (*S*-**8**) showed characteristic amide carbonyl absorption (1682 cm^{-1}) in its IR spectrum and resonance at 175.2 ppm in its ^{13}C-NMR spectrum. Moreover, as summarized in Table 1, ^{13}C-NMR spectral data of vasicol (*S*-**3b**) correspond well with those of deaminovasicol (*S*-**8**) in 2-pyrrolidinone moieties (**Table 1**). Since no similar tautomerism is possible for **8** as for **3b**, the above-mentioned evidence strongly suggests that our synthetic vasicol is present in the form of 2-pyrrolidinone (**3b**) instead of **3a**. In addition, comparing the ^{13}C-NMR spectral data of synthetic **3b** with those given for the natural products, reported respectively by Russian chemists[8] and Joshi *et al.*, [9] allows to conclude that their compounds (vasicol) also existed exclusively in the form of **3b**, and thus confirms the structural assignment made by Russian chemists.[8] This might also suggest that the structure (**3a**) presented by Joshi *et al.*[9] has been incorrectly assigned.



Scheme 3

Table 1. ^{13}C-NMR chemical shift of vasicol (**3**) and deaminovasicol (**8**) (in $CDCl_3$)

Position[a]	Position[b]	Tekzhene-tskaya's data of **3b**	Joshi's data of **3a**	Data of **3b** in this paper	Data of **8** in this paper	
5	1	42.5	43.1	43.1		43.1
4	2	28.0	27.6	27.6		27.7
3	3	69.0	69.9	70.0		70.0
2	3a	**174.3**	**175.2**	**175.1**		**175.2**
3'	4a	146.5	145.7	145.8		
4'	5	114.8	115.7	115.8		127.8
5'	6	128.6	129.5	129.6		128.2(2C)
6'	7	115.8	117.3	117.4		128.8(2C)
7'	8	130.1	131.2	131.3		135.7
2'	8a	118.8	118.4	118.6		
1'	9	43.3	44.7	44.8		47.0

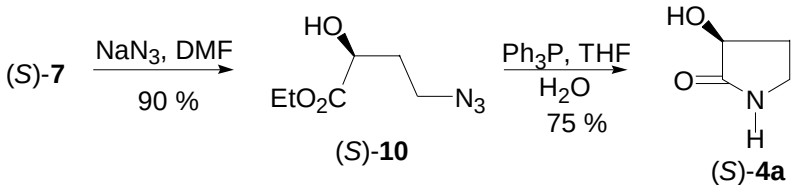
a. Numbered according to the ring system of assumed structure (**3a**)**;** b. Numbered according to structure (**3b**); c. NMR spectrometer model unspecified; d. Recorded on a BS567A instrument at a frequency of 25 MHz; e. Recorded on a Varian +500 instrument at a frequency of 125 MHz.

Since Indian authors did not report the amide carbonyl absorption band in the 1660-1690 cm^{-1} region in the IR spectra of both their vasicol (**3a**) and its *O*- and *N*-methyl derivatives, this might suggested that what they obtained was indeed **3a**. It is worth-mentioning that on transforming vasicine (**1**) to vasicol (**3a**), Indian chemists have isolated, in addition to **3a**, a less polar product ($C_{11}H_{14}N_2O_2$) from early fractions of the silica gel chromatography, which failed to crystallize. Although this compound was characterized solely by elementary analysis, it is possible that this compound was **3b**.

Taking into account that vasicol (**3a**) and (**3b**) are tautomers, they are interconvertible. The equilibrium between them would be acidity depending. While during the extraction and purification procedures, both acidification and basification have been employed,[7,8] as a result, the finally isolated vasicol could not reflect the real ratio of two tautomers (**3a**/**3b**) in the plant. However, Russian chemists' conclusion[8] that: "bases of the vasicol type are present in freshly obtained extracts of plants in small amounts and are, apparently, native alkaloid. When the combined alkaloids are stored for several years their amount increases appreciably" seems to be reasonable.

Finally, there are two points to be noted. First, although the Russian authors declared[8] that they have repeated the Indian authors' experiments, this was not indeed the case, since in addition to Indian chemists' silica gel column chromatographic purification (eluent, $CHCl_3$ / MeOH = 100 : 3) procedure,[7] Russian authors performed additional deposit filtration and alumina column chromatographic purification (using chloroform as eluent) procedures,[8] which might cause the loss of more polar component (**3a**). Second, the samples used by three research groups were of different origin. Indian authors used the extracts from roots of the plant *Adhatoda vasica*,[7] Joshi *et al.* used those from the leaves of the same plant,[9] while Russian authors used technical peganina extracted from *Peganum harmala*.[8]

Next, we turned our attention to the synthesis of (*S*)-3-hydroxy-2-pyrrolidinone (**4a**). Thus, the reaction of **5** with sodium azide in DMF afforded azide (**10**) in 90 % yield (**Scheme 4**). Treatment of azido ester (**10**) with triphenylphosphine led, *via* tandem Staudinger reaction[13]-cyclization, to the formation of **4a** in 75% yield. 3-Hydroxy-2-pyrrolidinone (**4a**) thus prepared exhibits mp 100-101 ^{o}C and $[\alpha]_D^{20}$ –125.3° (*c* 1.14, $CHCl_3$), which are in agreement with the literature values {mp 99 ^{o}C, $[\alpha]_D$ –125° (*c* 1.1, $CHCl_3$);[14] mp 103-104.5 ^{o}C, $[\alpha]_D^{25}$ –113° (*c* 0.77, $CHCl_3$)[15c]}. Comparing with other chiral synthesis[14,15] or enzymatic synthesis[16] of optically active **4a**, present synthesis used inexpensive and common chemicals, and thus is a practical method.



Scheme 4

CONCLUSION

In summary, starting from (*S*)-malic acid, a flexible approach to (3*S*)-3-hydroxy-2-pyrrolidinone (**4a**) and (*S*)-1-alkyl-3-hydroxy-2-pyrrolidinones (**4**) was developed. Present method not only led to the first total synthesis of (-)-(*S*)-vasicol, but also allowed the revision and clarification on the confusion about the structure of naturally occurring (*S*)-vasicol (**3a**/**3b**).

EXPERIMENTAL

Melting points were determined on a Yanaco MP-500 micro melting point apparatus. IR spectra were measured with a Nicolet Avatar 360 FT-IR spectrophotometer using film KBr pellet techniques. ^{1}H-NMR spectra were recorded in $CDCl_3$ on a Varian unity +500 spectrometer with tetramethylsilane as an internal standard. Chemical shifts are expressed in δ (ppm) units downfield from TMS. MS spectra were recorded by a Bruker Dalton Esquire 3000 plus liquid chromatography-mass Spectrum (ESI direct injection). Optical rotations were measured with Perkin-Elmer 341 automatic polarimeter. THF used in the reactions was dried by distillation over metallic sodium and benzophenone; CH_2Cl_2 were distilled over P_2O_5. Silica gel (Zhifu, 300~400 mesh) was used for column chromatography, eluting (unless otherwise stated) with EtOAc / petroleum ether (PE) (bp 60-90 °C) mixtures. (*S*)-**6** was prepared in three steps from (*S*)-malic acid.[12]

(S)-2-Acetoxy-4-methanesulfonyloxybutyric acid ethyl ester (7)

To a cooled (–20 °C) solution of (*S*)-**6** (9.97 g, 52.5 mmol) and Et_3N (11.0 mL, 79.3 mmol) in anhydrous CH_2Cl_2 (150 mL) was added dropwise MsCl (5.0 mL, 64.4 mmol). The mixture was warmed slowly to 0 °C over 4 h and then quenched with a 1 N aqueous solution of HCl (25 mL) and H_2O (10 mL). After separation the organic layer, the aqueous layer was extracted with CH_2Cl_2 (3×20 mL). The combined organic phase was washed successively with H_2O (40 mL), saturated aqueous $NaHCO_3$ (30 mL) and brine (20 mL), and then dried over anhydrous Na_2SO_4. After filtration, the filtrate was concentrated under reduced pressure, and the residue was purified by flash chromatography on silica gel (eluent: EtOAc / PE = 1 : 2) to afford (*S*)-**7** (11.95 g, 85.0 %) as a colorless oil. $[\alpha]_D^{20}$ – 22.7° (*c* 1.0, $CHCl_3$). IR (film) ν_{max}: 2985, 2941, 1790, 1743, 1469, 1434, 1374, 1356, 1234, 1175 cm^{-1}; ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.28 (t, *J* = 7.08 Hz, 3H, CH_3), 2.16 (s, 1H, $COCH_3$), 2.22-2.38 (m, 1H, H-3), 3.02 (s, 3H, SO_2CH_3), 4.22 (q, *J* = 7.08 Hz, 2H, OCH_2), 4.34 (t, *J* = 6.10 Hz, 2H, H-4), 5.14 (dd, *J* = 4.51, 8.19 Hz, 1H, H-2) ppm. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 14.1 (1C), 20.6 (1C), 30.6 (1C), 37.4 (1C), 61.9 (1C), 64.9 (C), 68.4 (1C), 169.3 (1C), 170.1 (1C) ppm. MS (ESI): 291 ($M+Na^+$, 100). HRMS calcd for $[C_9H_{16}O_7S+Na]^+$: 291.050. Found: 291.0509. Anal. Calcd for $C_9H_{16}NO_7S$: C, 40.3; H, 5.97. Found: C, 40.87; H, 5.73.

(S)-2-Hydroxy-4-methanesulfonyloxybutyric acid ethyl ester (5)

To an ice-bath cooled solution of **7** (5.0 g, 18.6 mmol) in ethanol (38 mL) was added dropwise AcCl (1.3 mL, 18.3 mmol) over a period of 15 min. After stirring at rt for 36 h, the mixture was neutralized with solid $NaHCO_3$, filtrated, and concentrated under reduced pressure. The residue was dissolved in CH_2Cl_2, and then filtrated over celite. The filtrate was concentrated and the residue was purified by flash chromatography on silica gel (eluent: EtOAc / PE = 1 : 1), which afforded **5** (3.79 g, 90 %) as a colorless oil. $[\alpha]_D^{20}$ –5.54° (*c* 1.0, $CHCl_3$). IR (film) ν_{max}: 3504, 2984, 2941, 2904, 2516, 2392, 2320, 2069, 1736, 1637, 1468, 1448, 1419, 1352, 1219, 1172, 1124, 1021, 974, 927, 843, 814, 736, 531 cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.28 (t, *J* = 7.14 Hz, 3H, CH_3), 2.04 (m, 1H, H-3), 2.24 (m, 1H, H-3), 3.00 (s, 3H, SO_2CH_3), 3.10 (s, 1H, OH), 4.24 (q, *J* = 7.14 Hz, 2H, OCH_2), 4.27 (dd, *J* = 4.12, 7.80 Hz, 1H, H-2), 4.36 (m, 2H, H-4) ppm. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 14.1 (1C), 33.3 (1C), 37.0 (1C), 62.2 (1C), 66.0 (1C), 66.5 (C), 174.4(1C) ppm. MS (ESI): 249 ($M+Na^+$, 100), 244 (M^++H_2O, 60), 227 ($M+H^+$, 20). Anal. Calcd for $C_7H_{14}NO_6S$: C, 37.17; H, 6.19. Found: C, 36.74; H, 6.21.

(S)-1-(2-Amino-benzyl)-3-hydroxypyrrolidin-2-one (Vasicol) (3b)

A mixture of **5** (280 mg, 1.24 mmol) and *o*-aminobenzylamine (300 mg, 2.46 mmol) in anhydrous THF (5.5 mL) was stirred at rt for 24 h. To this solution was added DMAP (147 mg, 1.20 mmol). After stirring

at rt for 7 days, the mixture was concentrated under reduced pressure and the residue was purified by flash chromatography on silica gel (eluent: $CHCl_3$ / MeOH = 30 : 1) to afford **3b** (116 mg, 51 %) as a pale yellow oil. $[\alpha]_D^{20}$ –90.4° (*c* 0.95, $CHCl_3$). IR (film) ν_{max}: 3354, 3231, 3063, 3017, 2928, 2875, 1674, 1606, 1583, 1495, 1459, 1305, 1256 cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 1.91 (m, 1H, H-4), 2.35 (m, 1H, H-4), 3.16 (m, 1H, H-5), 3.27 (m, 1H, H-5), 4.30 (d, *J* = 14.58 Hz, 1H, $PhCH_2$), 4.38 (d, *J* = 14.58 Hz, 1H, $PhCH_2$), 4.40 (br s, 1H, OH), 4.41 (t, *J* = 8.36 Hz, 1H, H-3), 4.70 (br s, 1H, NH_2), 6.65, 7.00, 7.10 (3m, 4H, Ph-H) ppm. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 27.6, 43.1, 44.8, 70.0, 115.8, 117.4, 118.6, 129.6, 131.3, 145.8, 175.1 ppm. MS (ESI): 229 ($M+Na^+$, 40), 207 ($M+H^+$, 100). Anal. Calcd for $C_{11}H_{14}N_2O_2$: C, 64.08; H, 6.80; N, 13.59. Found: C, 64.39; H, 7.09; N, 13.17.

(S)-1-Benzyl-3-hydroxypyrrolidin-2-one (8)

A neat mixture of ester (**7**) (5.57 g, 20.7 mmol) and benzylamine (6.8 mL, 62 mmol) was stirred at rt for 7 days. The resulting mixture was purified by flash chromatography on silica gel (eluent: EtOAc / PE = 2 : 1) to afford pyrrolidinone (**8**) (4.0 g, 83 %) as a white solid. mp 100-102 °C (CH_2Cl_2 / PE = 3 : 1). $[\alpha]_D^{20}$ -76.2° (*c* 1.03, $CHCl_3$). IR (film) ν_{max}: 3341, 3062, 3030, 2986, 2927, 2875, 1682, 1598, 1496, 1454, 1437, 1359, 1289, 1265, 1170 cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$), δ: 1.89 (dddd, *J* = 8.60, 9.34, 9.70, 12.70 Hz, 1H, H-4), 2.36 (dddd, *J* = 2.01, 6.96, 8.60, 12.70 Hz, 1H, H-4), 3.12 (ddd, *J* = 6.96, 9.70, 9.70 Hz, 1H, H-5), 3.19 (ddd, *J* = 2.01, 9.34, 9.70 Hz, 1H, H-5), 3.28 (br s, 1H, OH), 4.37 (t, *J* = 8.60 Hz, 1H, H-3), 4.39 (d, *J* = 14.70 Hz, 1H, $PhCH_2$), 4.44 (d, *J* = 14.70 Hz, 1H, $PhCH_2$), 7.10~7.30 (m, 5H, Ph-H) ppm. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 27.74 (1C), 43.10 (1C), 47.03 (1C), 70.02 (1C), 127.78 (1C), 128.16 (2C), 128.78 (2C), 135.72 (1C), 175.17 (C=O) ppm. MS (ESI): 214 ($M+Na^+$, 25), 192 ($M+H^+$, 100). HRMS calcd for $[C_{11}H_{13}NO_2+Na]^+$: 214.0838. Found: 214.0836. Anal. Calcd for $C_{11}H_{13}NO_2$: C, 69.09; H, 6.85; N, 7.32. Found: C, 69.19; H, 6.89; N, 7.56.

(S)-4-Azido-2-hydroxybutyric acid ethyl ester (10)

To a solution of **5** (3.0 g, 13.3 mmol) in DMF (40 mL) was added NaN_3 (1.7 g, 78.4 mmol) at rt. After stirred for 2 days, the mixture was quenched with H_2O (120 mL) and extracted with ether (5×30 mL). The combined organic phase was washed successfully with H_2O (30 mL) and brine (20 mL), and then dried over anhydrous Na_2SO_4. After filtrated and concentrated under reduced pressure, the residue was purified by flash chromatography on silica gel (eluent: EtOAc / PE = 1 : 6), which afforded **10** (2.1 g, 90 %) as a colorless oil. $[\alpha]_D^{20}$ + 4.32° (*c* 1.04, $CHCl_3$). IR (film) ν_{max}: 3468, 2982, 2630, 2875, 2101, 1734, 1539, 1455, 1369, 1263, 1219 cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$), δ: 1.32 (t, *J* = 7.14 Hz, 3H, CH_3), 1.90 (m, 1H, H-3), 2.09 (m, 1H, H-3), 2.95 (d, *J* = 4.91 Hz, 1H, OH), 3.48 (m, 2H, H-4), 4.27 (q, *J* = 7.14 Hz, 2H,

OCH_2), 4.23-4.31 (1H, H-2) ppm. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 14.1 (1C), 33.2 (1C), 47.3 (1C), 62.1 (1C), 67.6 (1C), 174.7(1C) ppm. MS (ESI): 191 (M^++H_2O, 80), 174 (M+H^+, 100).

(S)-3-Hydroxypyrrolidin-2-one (4a)

To a solution of (*S*)-**10** (7.6 g, 43.93 mmol) in THF (90 mL) was added PPh_3 (11.5 g, 43.84 mmol). After stirring at rt for 6 h, H_2O (20 mL, 11 mmol) was added dropwise, and stirring continued at the same temperature for another 2 days. The mixture was concentrated at reduced pressure. After addition of H_2O (20 mL), the aqueous phase was separated and washed successively with EtOAc (3×20 mL) and CH_2Cl_2 (3×20 mL). After concentrated at reduced pressure, the residue was recrystallized from Et_2O / EtOH to give (*S*)-**4a** (3.33 g, 75 %) as white crystals. mp 100-101 °C. $[\alpha]_D^{20}$ –125.3° (*c* 1.14, $CHCl_3$). [lit., mp 99 °C; $[\alpha]_D$ –125° (*c* 1.1, $CHCl_3$);[14] mp 103-104.5 °C; $[\alpha]_D^{25}$ –113° (*c* 0.77, $CHCl_3$)[15c] for (*S*)-**4a**; $[\alpha]_D^{22}$ +121.7° (*c* 2.07, $CHCl_3$).[16] mp 102-103 °C; $[\alpha]_D^{22}$ +121.9° (*c* 0.7, $CHCl_3$) for (*R*)- **4a**[15b]]. IR (film) ν_{max}: 3319, 3001, 2951, 2909, 1697, 1491, 1464, 1418, 1384, 1291, 1264 cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 2.06 (m, 1H, H-4), 2.48 (m, 1H, H), 3.31 (m, 1H, H-5), 3.41 (m, 1H, H-5), 4.35 (t, *J* = 8.55 Hz, 1H, H-3), 4.46 (br s, 1H, OH), 7.00 (br s, 1H, NH) ppm. ^{13}C-NMR (125 MHz, $CDCl_3$) δ: 30.0 (1C), 38.8 (1C), 69.1 (1C), 179.0 (1C) ppm. MS (ESI): 225 (2M+Na^+, 40), 203 (2M+H^+, 50), 124 (M+Na^+, 100), 119 (M^++H_2O, 25), 102(M+H^+, 95).

ACKNOWLEDGEMENTS

The authors are grateful to the NNSF of China and the Fund for doctoral sites by the Ministry of Education for financial support.

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