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ARTICLE

Synthesis of Functionalized 2-Vinyl-2,3-dihydropyrroles and 3-Methylene-1,2,3,4-tetrahydropyridines by Palladium-Catalyzed Cyclization of β-Enaminocarbonyl Compounds with Allylic Bisacetates

Cite this: DOI: 10.1039/xoxxoooooox

Received ooth January 2012,
Accepted ooth January 2012

DOI: 10.1039/xoxxoooooox

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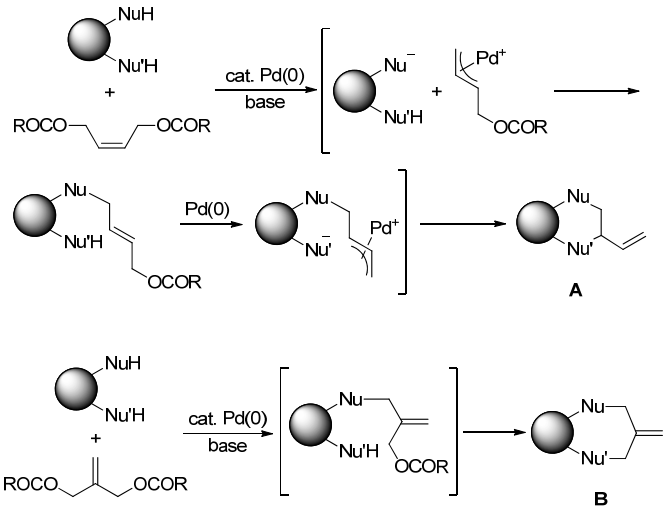
A palladium-catalyzed cyclization of β-enaminocarbonyl compounds with allylic bisacetates is described. 2-Vinyl-2,3-dihydropyrroles and 3-methylene-1,2,3,4-tetrahydropyridines were produced from the reaction of β-enaminocarbonyl compounds with 1,4-diacetoxy-2-butene and 2-methylene-1,3-propanediol diacetate, respectively.

Introduction

Substituted dihydropyrroles and tetrahydropyridines are an important class of heteroaromatic molecules, which are components in a variety of biologically active natural products and pharmaceutical agents.[1,2] Furthermore, some of their derivatives serve as excellent intermediates for various nitrogen-containing heterocyclic molecules of synthetic and biological interest.[3,4] For this reason, extensive studies have been devoted toward finding syntheses of substituted dihydropyrroles and tetrahydropyridines.[5,6]
Palladium-catalyzed allylic substitution reactions with nucleophiles have received considerable attention because of their versatile and specific reactivities. A large number of transformations including cyclization reactions have been developed by using various allylic substrates and nucleophiles.[7] For example, a 1,4-diacyloxy-2-butene reacts with bis-nucleophile that contains two nucleophilic parts within the molecule, to afford a cyclized product **A** via successive double allylic substitutions (Scheme 1). Similarly, reaction of a 2-methylene-1,3-propanediol diester with bis-nucleophile produces a cyclized compound **B**. A variety of classes of cyclic molecules have been synthesized by the suitable design of bis-nucleophiles.[8,9] During the course of our studies on the palladium-catalyzed reactions of propargylic esters with bis-nucleophiles,[10] we focused on the nucleophilic activity of β-enaminocarbonyl compounds[10h] towards the 1,4-diacyloxybut-2-ene and the 2-methylene-1,3-propanediol diester. Herein, we describe palladium-catalyzed reactions of β-enaminocarbonyl compounds **1** with 1,4-diacetoxybut-2-ene (**2**) and 2-methylene-1,3-propanediol diacetate (**4**), in which the 2-vinyl-2,3-dihydropyrroles **3** and 3-methylene-1,2,3,4-tetrahydropyridines **5** have been constructed in one step, respectively (Scheme 2).



Scheme 1 Palladium-catalyzed cyclizations of allylic bisacetates with bis-nucleophiles.

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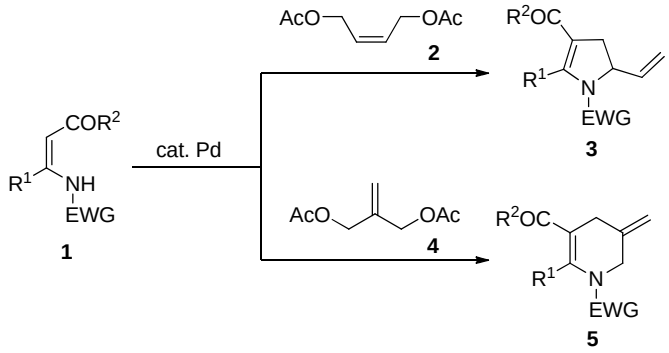
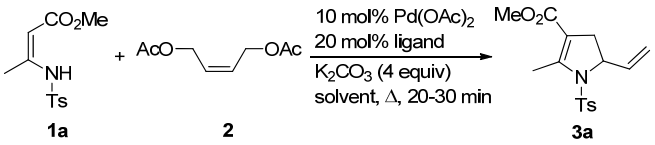


Scheme 2 Synthesis of 2-vinyl-2,3-dihydropyrroles **3** and 3-methylene-1,2,3,4-tetrahydropyridines **5**.

Results and discussion

We began our studies using tosyl-substituted β-enamino ester **1a** and (*Z*)-1,4-diacetoxybut-2-ene (**2**). When **1a** and **2** were subjected to the reaction with 10 mol % of $Pd(OAc)_2$, 20 mol % of 1,3-Bis(diphenylphosphino)propane (DPPP) and 4 equiv K_2CO_3 in THF under reflux conditions for 20 min, the 2-vinyl-2,3-dihydropyrrole **3a** was produced in 26% yield (entry 1 in Table 1). Experimenting with reaction solvents (entries 2–5) revealed that the yield was increased to 63% in the case of dioxane (entry 5). After attempts employing various phosphine ligands (entries 6–9), we found that **3a** was produced in 95% yield when the reaction was carried out in the presence of (±)-2,2'-bis(diphenylphosphino)-1,1'-binaphthyl (BINAP) (entry 9).

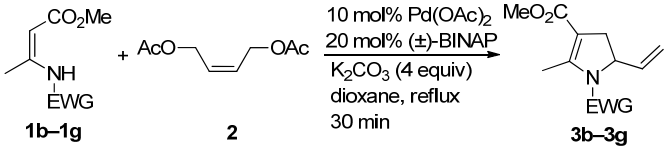
Table 1. Initial attempts using **1a** with **2**



Entry	Solvent	Ligand	Temp (ºC)	Yield (%)
1	THF	DPPP	reflux	26
2	DMF	DPPP	120	43
3	NMP	DPPP	120	44
4	MeCN	DPPP	reflux	56
5	dioxane	DPPP	reflux	63
6	dioxane	DPPB	reflux	31
7	dioxane	DPPE	reflux	78
8	dioxane	DPPF	reflux	85
9	dioxane	(±)-BINAP	reflux	95

Having identified a useful set of reaction conditions, we next carried out a study using β-enamino esters **1b–1g** containing various sulfonyl groups on the amino moiety (Table 2). When substrate **1b** having a benzenesulfonyl group was subjected to the reaction with allylic bisacetate **2**, the 2-vinyl-2,3-dihydropyrrole **3b** was produced in 88% yield (entry 1 in Table 1). The reaction using mesyl-substituted β-enamino ester **2c** also proceeded to afford the corresponding product **3c** in 96% yield (entry 2). Similar results were obtained in the reaction of the substrates having a 2-naphthalenesulfonyl, 2-nitrobenzenesulfonyl (Ns) and 4-nitrobenzenesulfonyl (Nos) group to afford the corresponding products **3d**, **3e** and **3f** in good yield, respectively (entries 3–5). Furthermore, the yield of the corresponding product **3g** was increased to 99% yield when 2,4,6-trimethylbenzenesulfonyl-substituted substrate **1g** was used (entry 6).[11]

Table 2. Reactions using various substrates **1b–1g** with **2**.



Entry	EWG	Yield of **3** (%)
1	benzenesulfonyl (**1b**)	88
2	methanesulfonyl (Ms) (**1c**)	96
3	2-naphthalenesulfonyl (**1d**)	86
4	2-nitrobenzensulfonyl (Ns) (**1e**)	82
5	4-nitrobenzensulfonyl (Nos) (**1f**)	74
6	2,4,6-trimethylbenzenesulfonyl (**1g**)	99

We next conducted the reactions using various β-enaminocarbonyl compounds **1h–1p** (Table 3). When β-enamino isopropyl ester (**1h**) and **2** were exposed to the optimal conditions, the 2-vinyl-2,3-dihydropyrrole **3h** was obtained in 92% yield (entry 1). The propyl-substituted substrate **1i** uneventfully reacted to afford the corresponding product **3i** in 90% yield (entry 2), but the yield of the corresponding product **3j** was decreased in the case of isopropyl-substituted substrate **1j** (entry 3), presumably because of the bulkiness of the isopropyl moiety. The phenyl-substituted β-enamino ester **1k** successfully reacted with **2** to produce the corresponding product **3k** in 99% yield (entry 4). Similarly, the reactions of the substrates **1l–1n** having a various aryl group proceeded to give the corresponding products **3l–3n** in high yields (entries 5–7). When the β-enamino ketones **1o** and **1p** were subjected to the reaction, the corresponding cyclized products **3o** and **3p** were obtained in 91% and 89% yield, respectively (entries 8 and 9).

A plausible mechanism for the cyclization process is shown in Scheme 3. In the presence of a palladium catalyst, 1,4-diacetoxybut-2-ene **2** is transformed to the π-allylpalladium complex **6**, which causes the nucleophilic attack of the β-enaminocarbonyl compound to afford the substituted allylic acetate **7**. The compound **7** is successively subjected to the intramolecular nucleophilic attack of the enamino moiety by palladium via the formation of π-allylpalladium intermediate **8** to produce the dihydropyrrole **3**.

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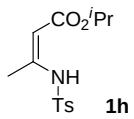
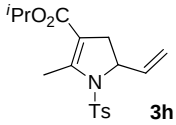
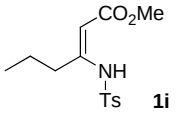
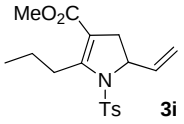
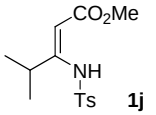
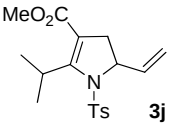
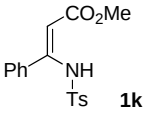
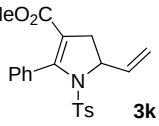
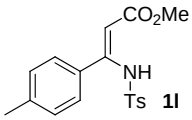
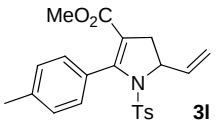
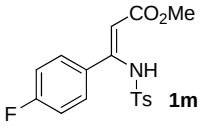
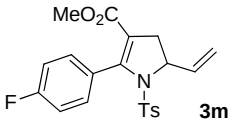
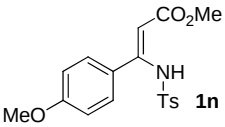
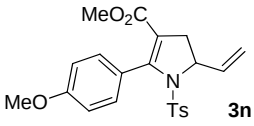
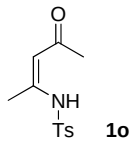
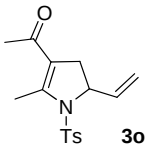
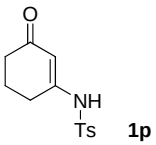
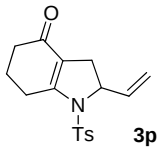
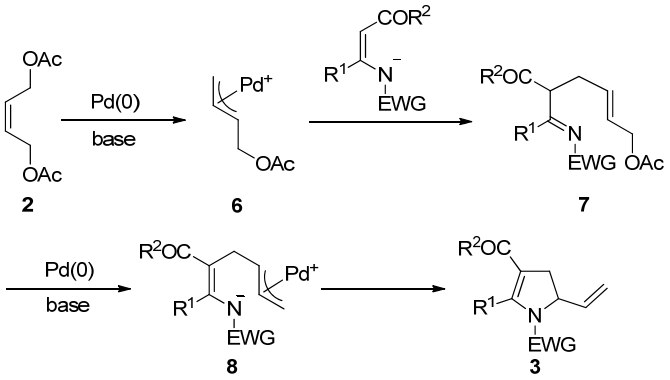
Table 3. Reactions using various substrates **1h–1p** with **2**

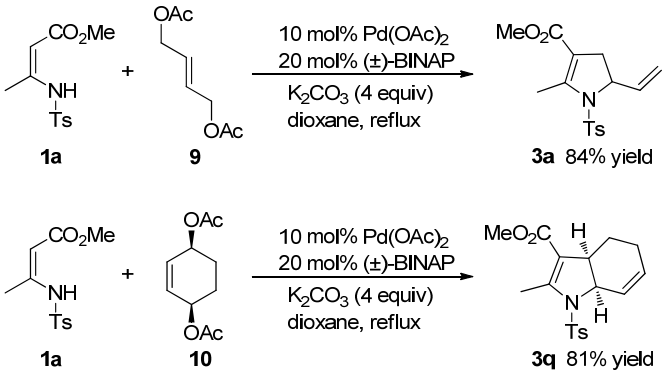
Entry	Substrate **1**	Product **3**	Yield (%)
1	 **1h**	 **3h**	92
2	 **1i**	 **3i**	90
3	 **1j**	 **3j**	36
4	 **1k**	 **3k**	99
5	 **1l**	 **3l**	96
6	 **1m**	 **3m**	98
7	 **1n**	 **3n**	93
8	 **1o**	 **3o**	91
9	 **1p**	 **3p**	89

[a]All reactions were carried out with **2** in the presence of 10 mol % $Pd(OAc)_2$, 20 mol% (±)-BINAP and 4 equiv K_2CO_3 in dioxane under reflux for 30 min.



Scheme 3 Proposed mechanism for the production of **3**.

We next examined the reactions using other allylic 1,4-bisacetates (Scheme 4). When the palladium-catalyzed reaction of (*E*)-1,4-diacetoxy-2-butene (**9**) with β-enamino ester **1a** was carried out, the 2-vinyl-2,3-dihydropyrrole **3a**, which was the same product from the reaction of (*Z*)-substrate **2**, was obtained in 84% yield. This result indicates that the reactions proceeded via the formation of a common π-allylpalladium intermediate **6** as shown in Scheme 3, regardless of the stereochemistry of the allylic bisacetates. The *cis*-cyclohexene diacetate **10** also reacted with **1a** to afford the *cis*-fused tetrahydroindole **3q** in a stereospecific manner. This result demonstrates that the nucleophilic substitution process proceeded with the overall retention of the stereochemistry.



Scheme 4 Reactions using allylic bisacetates **9** and **10** with **1a**.

We next turned our attention to the reaction with the 2-methylene-1,3-propanediol diester. When 2-methylene-1,3-propanediol diacetate (**4**) and β-enamino ester **1a** were treated with 10 mol % $Pd(OAc)_2$, 20 mol % (±)-BINAP and 4 equiv K_2CO_3 in dioxane under reflux conditions, the reaction successfully proceeded to produce the 3-methylene-1,2,3,4-tetrahydropyridine **5a** in 98% yield (Scheme 5).

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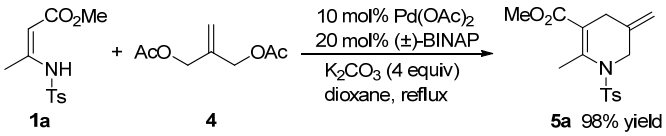
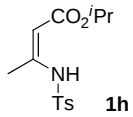
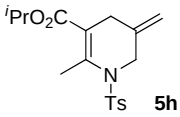
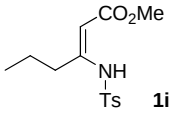
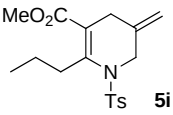
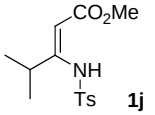
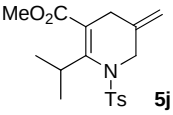
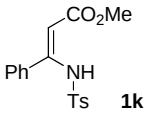
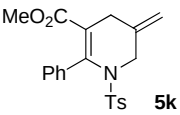
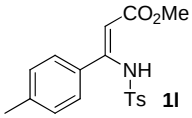
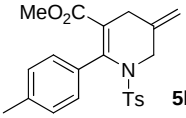
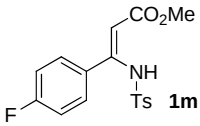
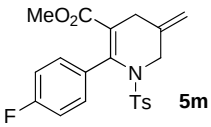
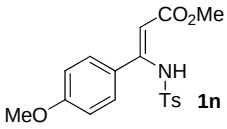
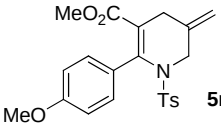
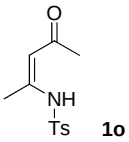
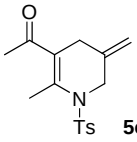
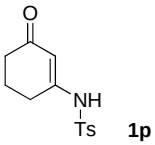
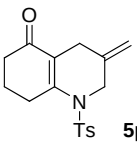


Scheme 5 Reaction of allylic bisacetate **4** with **1a**.

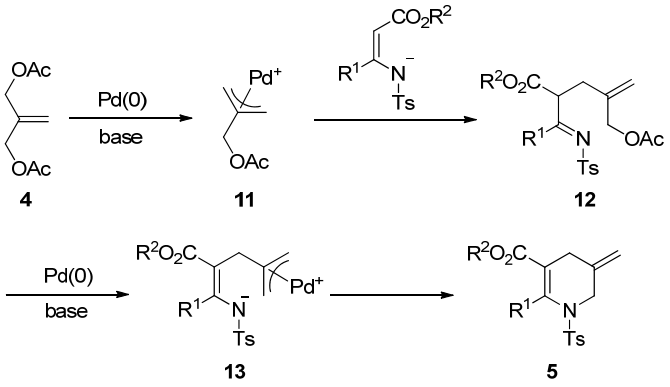
Table 4. Reactions using various substrates **1h–1p** with **4**

Entry	Substrate **1**	Product **5**	Yield (%)
1	 **1h**	 **5h**	99
2	 **1i**	 **5i**	94
3	 **1j**	 **5j**	75
4	 **1k**	 **5k**	99
5	 **1l**	 **5l**	95
6	 **1m**	 **5m**	94
7	 **1n**	 **5n**	96
8	 **1o**	 **5o**	87
9	 **1p**	 **5p**	91

[a]All reactions were carried out with **4** in the presence of 10 mol % $Pd(OAc)_2$, 20 mol% (±)-BINAP and 4 equiv K_2CO_3 in dioxane under reflux for 30 min.

Reactions of various β-enaminocarbonyl compounds **1h–1p** with **4** are summarized in Table 4. When β-enamino isopropyl ester (**1h**) was subjected to the reaction, the 3-methylene-1,2,3,4-tetrahydropyridine **5h** was produced in 99% yield (entry 1). The propyl- and isopropyl-substituted substrates **1i** and **1j** were successfully transformed to the cyclized products **5i** and **5j** in 94% and 75% yield, respectively (entries 2 and 3). The reactions of β-enamino esters **1k–1n** which have a various aryl group also proceeded to give the corresponding products **5k–5n** in high yield, respectively (entries 4–7). Similarly, the β-enamino ketones **1o** and **1p** were uneventfully converted to the corresponding cyclized products **5o** and **5p** in 87% and 91% yield, respectively (entries 8 and 9).

A plausible mechanism for the production of 3-methylene-1,2,3,4-tetrahydropyridine **5** is shown in Scheme 6. By reacting with a palladium catalyst, 2-methylene-1,3-propanediol diester **4** is converted to the π-allylpalladium complex **11**, which is subjected to the nucleophilic attack of the β-enaminocarbonyl compound to afford the substituted allylic acetate **12**. Then intramolecular nucleophilic cyclization of **12** occurs via the intermediate **13** by further reacting with palladium to produce the 3-methylene-1,2,3,4-tetrahydropyridine **5**.



Scheme 6 Proposed mechanism for the production of **5**.

Conclusions

In conclusion, the effort described above has led to the development of a palladium-catalyzed reaction of β-enaminocarbonyl compounds with allylic bisacetates. This process affords 2-Vinyl-2,3-dihydropyrroles and 3-methylene-1,2,3,4-tetrahydropyridines having a variety of substituents via a successive nucleophilic cyclization. Since many biologically active molecules containing a pyrrolidine and piperidine component have been reported, our methodology could provide a new protocol for the synthesis of these compounds.

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Experimental

General experimental

All nonaqueous reactions were carried out under a positive atmosphere of argon in dried glassware unless otherwise indicated. Materials were obtained from commercial suppliers and used without further purification except when otherwise noted. Solvents were dried and distilled according to standard protocol.

General procedure for the synthesis of β-enamino esters 1

To a stirred solution of ethyl acetoacetate (1.0 mL, 9.31 mmol) in benzene (40 mL) were added *p*-toluenesulfoneamide (1.67 g, 9.77 mmol), *p*-TsOH·H2O (89.0 mg, 465 μmol) at rt. After stirring was continued for 13 h under reflux condition with a Dean-Stark trap, the reaction mixture was concentrated. After filtration of the residue using small amount of silica gel followed by concentration, the residue was recrystallized by AcOEt to give the β-enamino ester **1a** (1.44 g, 57%) as colorless crystals.

(*Z*)-Methyl 3-(4-methylphenylsulfonamido)but-2-enoate (1a). Yield 57%; colorless crystals (AcOEt, mp. 75.2−76.8 ºC); IR (neat): 1672, 1626, 1256, 1164 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.03 (3H, s), 2.43 (3H, s), 3.70 (3H, s), 4.90 (1H, s), 7.32 (2H, d, *J* = 8.2 Hz), 7.78 (2H, d, *J* = 8.2 Hz), 11.10 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 19.7 (CH_3), 21.5 (CH_3), 51.2 (CH_3), 95.9 (CH), 127.1 (CH), 129.9 (CH), 137.6 (Cq), 144.2 (Cq), 152.9 (Cq), 169.4 (Cq); HRMS (ESI) *m/z* calcd for $C_{12}H_{16}NO_4S$ $[M+H]^+$ 270.0800, found 270.0800.

(*Z*)-Methyl 3-(phenylsulfonamido)but-2-enoate (1b). Yield 69%; colorless crystals (AcOEt, mp. 40.0−42.2 ºC); IR (neat): 1672, 1627, 1257, 1168 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.04 (3H, s), 3.71 (3H, s), 4.93 (1H, s), 7.52–7.56 (2H, m), 7.60–7.62 (1H, m), 7.89–7.92 (2H, m), 11.16 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 19.7 (CH_3), 51.2 (CH_3), 96.1 (CH), 127.0 (CH), 129.3 (CH), 133.3 (CH), 140.4 (Cq), 152.7 (Cq), 169.4 (Cq); HRMS (ESI) *m/z* calcd for $C_{11}H_{13}NO_4SNa$ $[M+Na]^+$ 278.0463, found 278.0460.

(*Z*)-Methyl 3-(methylsulfonamido)but-2-enoate (1c). Yield 49%; colorless crystals (AcOEt, mp. 40.7−44.3 ºC); IR (neat): 1673, 1626, 1257, 1154 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.24 (3H, s), 3.14 (3H, s), 3.71 (3H, s), 5.03 (1H, s), 10.90 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 19.7 (CH_3), 43.0 (CH_3), 51.3 (CH_3), 96.2 (CH), 152.5 (Cq), 169.4 (Cq); HRMS (ESI) *m/z* calcd for $C_6H_{12}NO_4S$ $[M+H]^+$ 194.0487, found 194.0488.

(*Z*)-Methyl 3-(naphthalene-2-sulfonamido)but-2-enoate (1d). Yield 53%; colorless crystals (AcOEt, mp. 63.4−66.3 ºC); IR (neat): 1671, 1626, 1256, 1164 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.07 (3H, s), 3.71 (3H, s), 4.91 (1H, s), 7.61–7.69 (2H, m), 7.85 (1H, dd, *J* = 2.0 and 8.4 Hz), 7.92 (1H, d, *J* = 8.4 Hz), 7.98 (2H, d, *J* = 8.4 Hz), 8.48 (1H, d, *J* = 2.0 Hz), 11.24 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 19.7 (CH_3), 51.2 (CH3), 96.1 (CH), 122.1 (CH), 127.8 (CH), 127.9 (CH), 128.5 (CH), 129.2 (CH), 129.3 (CH), 129.8 (CH), 132.0 (Cq), 135.0 (Cq), 137.3 (Cq), 152.7 (Cq), 169.4 (Cq); HRMS (ESI) *m/z* calcd for $C_{15}H_{16}NO_4S$ $[M+H]^+$ 306.0800, found 306.0804.

(*Z*)-Methyl 3-(2-nitrophenylsulfonamido)but-2-enoate (1e). Yield 59%; pale green crystals (AcOEt, mp. 90.1−91.6 ºC); IR (neat): 1676, 1629, 1542, 1255, 1172 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.17 (3H, s), 3.74 (3H, s), 5.01 (1H, s), 7.76−7.79 (2H, m), 7.89–7.91 (1H, m), 8.16–8.18 (1H, m), 11.62 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 20.0 (CH_3), 51.4 (CH_3), 97.4 (CH), 125.6 (CH), 130.5 (CH), 132.8 (CH), 134.2 (Cq), 134.3 (CH), 148.0 (Cq), 151.2 (Cq), 168.9 (Cq); HRMS (ESI) *m/z* calcd for $C_{11}H_{12}N_2O_6SNa$ $[M+Na]^+$ 323.0314, found 323.0312.

(*Z*)-Methyl 3-(4-nitrophenylsulfonamido)but-2-enoate (1f). Yield 67%; pale yellow crystals (AcOEt, mp. 102.9−105.7 ºC); IR (neat): 1672, 1629, 1533, 1257, 1168 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.06 (3H, s), 3.82 (3H, s), 5.01 (1H, s), 8.09 (2H, dt, *J* = 8.8 and 2.0 Hz), 8.39 (2H, dt, *J* = 8.8 and 2.0 Hz), 11.35 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 19.8 (CH_3), 51.5 (CH_3), 97.7 (CH), 124.7 (CH), 128.4 (CH), 146.0 (Cq), 150.3 (Cq), 151.7 (Cq), 169.4 (Cq); HRMS (ESI) *m/z* calcd for $C_{11}H_{12}N_2O_6SNa$ $[M+Na]^+$ 323.0314, found 323.0314.

(*Z*)-Methyl 3-(2,4,6-trimethylphenylsulfonamido)but-2-enoate (1g). Yield 66%; colorless crystals (AcOEt/hexane, mp. 113.1−116.7 ºC); IR (neat): 1669, 1624, 1345, 1277, 1159 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 1.93 (3H, s), 2.31 (3H, s), 2.65 (6H, s), 3.70 (3H, s), 4.85 (1H, s), 6.97 (2H, s), 11.20 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 18.9 (CH_3), 21.0 (CH_3), 22.5 (CH_3), 51.1 (CH_3), 94.3 (CH), 132.2 (CH), 134.7 (Cq), 139.0 (Cq), 143.1 (Cq), 153.0 (Cq), 169.5 (Cq); HRMS (ESI) *m/z* calcd for $C_{14}H_{20}NO_4S$ $[M+H]^+$ 298.1113, found 298.1112

(*Z*)-Isopropyl 3-(4-methylphenylsulfonamido)but-2-enoate (1h). Yield 31%; colorless crystals (AcOEt, mp. 65.7−67.8 ºC); IR (neat): 1665, 1626, 1258, 1165 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 1.24 (6H, d, *J* = 6.4 Hz), 2.02 (3H, s), 2.43 (3H, s), 4.87 (1H, s), 5.03 (1H, septet, *J* = 6.4 Hz) 7.32 (2H, d, *J* = 8.4 Hz), 7.78 (2H, d, *J* = 8.4 Hz), 11.20 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 19.6 (CH_3), 21.5(CH_3), 21.8 (CH_3), 67.4(CH), 96.9 (CH), 127.1 (CH), 129.9 (CH), 137.7 (Cq), 144.1 (Cq), 152.4 (Cq), 168.6 (Cq); HRMS (ESI) *m/z* calcd for $C_{14}H_{20}NO_4S$ $[M+H]^+$ 298.1113, found 298.1114.

(*Z*)-Methyl 3-(4-methylphenylsulfonamido)hex-2-enoate (1i). Yield 45%; colorless crystals (AcOEt, mp. 84.5−86.1 ºC); IR (neat): 1674, 1623, 1236, 1160 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 0.87 (3H, t, *J* = 7.4 Hz), 1.48 (2H, sextet, *J* = 7.4 Hz), 1.54 (3H, s), 2.34 (2H, t, *J* = 7.4 Hz), 3.70 (3H, s), 4.95 (1H, s), 7.31 (2H, d, *J* = 7.6 Hz), 7.76 (2H, d, *J* = 7.6 Hz), 11.02 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 13.5 (CH_3), 21.0 (CH_2), 21.5 (CH_3), 34.1 (CH_2), 51.2 (CH_3), 95.8 (CH), 127.1 (CH), 129.9 (CH), 137.5 (Cq), 144.1 (Cq), 157.4 (Cq), 169.6 (Cq); HRMS (ESI) *m/z* calcd for $C_{14}H_{20}NO_4S$ $[M+H]^+$ 298.1113, found 298.1114.

(*Z*)-Methyl 4-methyl-3-(4-methylphenylsulfonamido)pent-2-enoate (1j). Yield 39%; colorless crystals (AcOEt, mp. 64.9−68.6 ºC); IR (neat): 1673, 1621, 1240, 1165 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 1.00 (6H, d, *J* = 6.8 Hz), 2.43 (3H, s), 3.11 (1H, septet, *J* = 6.8 Hz), 3.70 (3H, s), 5.02 (1H, s), 7.31 (2H, d, *J* = 8.0 Hz), 7.75 (2H, d, *J* = 8.0 Hz), 11.01 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 21.5 (CH_3), 21.8 (CH_3), 29.4 (CH), 51.3 (CH_3), 94.0 (CH), 127.1 (CH), 129.8 (CH), 137.5 (Cq), 144.1 (Cq), 164.4 (Cq), 169.9 (Cq); HRMS (ESI) *m/z* calcd for $C_{14}H_{20}NO_4S$ $[M+H]^+$ 298.1113, found 298.1110.

(*Z*)-Methyl 3-(4-methylphenylsulfonamido)-3-phenylacrylate (1k). Yield 30%; colorless crystals (AcOEt/hexane, mp. 130.9−132.0 ºC); IR (neat): 1667, 1621, 1282, 1166 cm^{-1}; ^{1}H-NMR

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(400 MHz, CDCl3) δ 2.40 (3H, s), 3.71 (3H, s), 5.19 (1H, s), 7.18 (2H, d, *J* = 8.0 Hz), 7.25−7.34 (4H, m), 7.37−7.45 (3H, m), 10.65 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 21.6 (CH_3), 51.5 (CH_3), 101.5 (CH), 127.5 (CH), 127.8 (CH), 128.8 (CH), 129.3 (CH), 130.5 (CH), 133.8 (Cq), 136.4 (Cq), 144.0 (Cq), 155.1 (Cq), 168.7 (Cq); HRMS (ESI) *m/z* calcd for $C_{17}H_{18}NO_4S$ $[M+H]^+$ 332.0957, found 332.0953.

(*Z*)-Methyl 3-(4-methylphenylsulfonamido)-3-(p-tolyl)acrylate (1l). Yield 32%; colorless crystals (Et2O/hexane, mp. 110.6−114.3 ºC); IR (neat): 1673, 1618, 1285, 1166 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.38 (3H, s), 2.41 (3H, s), 3.70 (3H, s), 5.18 (1H, s), 7.12 (2H, d, *J* = 8.0 Hz), 7.16−7.23 (4H, m), 7.42 (2H, d, *J* = 7.6 Hz) 10.60 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 21.4 (CH_3), 21.5 (CH_3), 51.4 (CH_3), 101.2 (CH), 127.5 (CH), 128.6 (CH), 128.8 (CH), 129.3 (CH), 131.1 (Cq), 136.4 (Cq), 140.9 (Cq), 144.0 (Cq), 155.2 (Cq), 168.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{19}NO_4SNa$ $[M+Na]^+$ 368.0932, found 368.0935.

(*Z*)-Methyl 3-(4-fluorophenyl)-3-(4-methylphenylsulfonamido)acrylate (1m). Yield 32%; colorless crystals (Et2O/hexane, mp. 128.0−129.4 ºC); IR (neat): 1683, 1622, 1507, 1284, 1167 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.41 (3H, s), 3.71 (3H, s), 5.17 (1H, s), 6.97−7.04 (2H, m), 7.20 (2H, d, *J* = 7.2 Hz), 7.26−7.33 (2H, m), 7.41 (2H, d, *J* = 7.8 Hz), 10.63 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 21.6 (CH_3), 51.6 (CH_3), 101.6 (CH), 115.0 (CH, d, *J* = 22.3 Hz), 127.5 (CH), 129.4 (CH), 129.9 (Cq, d, *J* = 3.3 Hz), 130.9 (CH, d, *J* = 8.2 Hz), 136.3 (Cq), 144.2(Cq), 154.0 (Cq), 164.1 (Cq, d, *J* = 249.4 Hz), 168.6 (Cq); HRMS (ESI) *m/z* calcd for $C_{17}H_{17}NO_4FS$ $[M+H]^+$ 350.0862, found 350.0865.

(*Z*)-Methyl 3-(4-methoxyphenyl)-3-(4-methylphenylsulfonamido)acrylate (1n). Yield 34%; colorless crystals (AcOEt, mp. 128.2−131.2 ºC); IR (neat): 1671, 1616, 1285, 1167 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 2.40 (3H, s), 3.69 (3H, s), 3.84 (3H, s), 5.16 (1H, s), 6.83 (2H, d, *J* = 8.4 Hz), 7.18 (2H, d, *J* = 8.4 Hz), 7.27 (2H, d, *J* = 8.4 Hz), 7.41 (2H, d, *J* = 8.4 Hz), 10.58 (1H, brs); ^{13}C-NMR (100 MHz, CDCl3) δ 21.6 (CH_3), 51.4 (CH_3), 55.3 (CH_3), 100.7 (CH), 113.3 (CH), 126.1 (Cq), 127.5 (CH), 129.3 (CH), 130.5 (CH), 136.2 (Cq), 144.0 (Cq), 154.9 (Cq), 161.6 (Cq), 168.9 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{19}NO_5S$ $[M]^+$ 361.0984, found 361.0986.

(*Z*)-4-Methyl-N-(4-oxopent-2-en-2-yl)benzenesulfonamide (1o). Yield 35%; colorless crystals (AcOEt, mp. 71.8−74.3 ºC); IR (neat): 1643, 1586, 1254, 1163 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.04 (3H, s), 2.11 (3H, s), 2.43 (3H, s), 5.32 (1H, s), 7.32 (2H, d, *J* = 8.4 Hz), 7.78 (2H, d, *J* = 8.4 Hz), 12.74 (1H, brs); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 19.5 (CH_3), 21.5 (CH_3), 30.0 (CH_3), 104.5 (CH), 127.2 (CH), 129.9 (CH), 137.6 (Cq), 144.3 (Cq), 153.8 (Cq), 199.5 (Cq); HRMS (ESI) *m/z* calcd for $C_{12}H_{15}NO_3S$ $[M+Na]^+$ 276.0670, found 276.0671.

4-Methyl-*N*-(3-oxocyclohex-1-en-1-yl)benzenesulfonamide (1p). To a stirred solution of 3-aminocyclohex-2-enone (2.78 g, 25.0 mmol) in THF (200 mL) were added NaH (60% in oil) (3.00 g, 75.0 mmol) at rt. After stirring was continued for 1 h under reflux condition, TsCl (4.77 g, 25.0 mmol) in THF (50 mL) was added dropwise, and further stirring was continued for 4 h under reflux condition. The reaction mixture was quenched with 2 N HCl aq, and then extracted with AcOEt followed by concentration. The residue was recrystallized by AcOEt to give cyclic β-enamino ketone **1p** (4.05 g, 61%). Colorless crystals (AcOEt, mp. 212.4−215.9 ºC); IR (neat): 1600, 1345, 1160 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl3) δ 1.95 (2H, quint, *J* = 6.3 Hz), 2.27 (2H, t, *J* = 6.3 Hz), 2.32 (2H, t, *J* = 6.3 Hz), 2.45 (3H, s), 5.81 (1H, s), 6.76 (1H, brs), 7.33−7.37 (2H, m), 7.80−7.84 (2H, m); ^{13}C-NMR (100 MHz, CDCl3) δ 21.2 (CH_2), 21.7 (CH_3), 28.2 (CH_2), 36.2 (CH_2), 108.9 (CH), 127.7 (CH), 130.1 (CH), 135.3 (Cq), 145.2 (Cq), 154.3 (Cq), 198.2 (Cq); HRMS (ESI) *m/z* calcd for $C_{13}H_{15}NO_3SNa$ $[M+Na]^+$ 288.0670, found 288.0668.

General procedure for the synthesis of 2-vinyl-2,3-dihydropyrroles 3 (Table 1, entry 9)

To a stirred solution of β-enamino ester (80.8 mg, 300 μmol) in dioxane (3.0 mL) were added (*Z*)-1,4-diacetoxybut-2-ene (**2**) (62.0 mg, 360 μmol), $Pd(OAc)_2$ (6.7 mg, 30.0 μmol), (±)-BINAP (37.4 mg, 60.0 μmol) and K_2CO_3 (166 mg, 1.20 mmol) at rt, and stirring was continued for 30 min at the same temperature under argon atmosphere. The reaction mixture was then allowed to heat to 120 ºC, and stirring was continued for 30 min. After filtration of the reaction mixture using small amount of silica gel followed by concentration, the residue was chromatographed on silica gel with AcOEt–hexane (1:6 v/v) as eluent to give the 2-vinyl-2,3-dihydropyrrole **3a** (91.3 mg, 284 μmol, 95%) as colorless needles.

Methyl 2-methyl-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3a). Yield 95%; colorless needles (AcOEt, mp. 91.9–93.2 ºC); IR (neat) 1705, 1635, 1167, 1103 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.39–2.45 (1H, m), 2.43 (3H, s) 2.47 (3H, t, *J* = 1.8 Hz), 2.79–2.87 (1H, m), 3.67 (3H, m), 4.70–4.75 (1H, m), 5.18 (1H, d, *J* = 10.0 Hz), 5.33 (1H, d, *J* = 16.8 Hz), 5.88 (1H, ddd, *J* = 6.4, 10.0 and 16.8 Hz), 7.31 (2H, d, *J* = 8.4 Hz), 7.70 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.3 (CH_3), 21.5 (CH_3), 34.4 (CH_2), 51.1 (CH_3), 63.0 (CH), 110.0 (Cq), 115.8 (CH_2), 127.1 (CH), 129.9 (CH), 136.7 (Cq), 137.5 (CH), 144.2 (Cq), 151.0 (Cq), 166.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{16}H_{19}NO_4S$ $[M]^+$ 321.1035, found 321.1032.

Methyl 2-methyl-1-(phenylsulfonyl)-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3b). Yield 88%; yellow oil; IR (neat) 1706, 1636, 1170, 1105 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.40–2.45 (1H, m), 2.48 (3H, t, *J* = 1.8 Hz), 2.79–2.87 (1H, m), 3.68 (3H, s), 4.72–4.77 (1H, m), 5.19 (1H, d, *J* = 10.0 Hz), 5.34 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 6.4, 10.0 and 16.8 Hz), 7.51–7.55 (2H, m), 7.59–7.64 (1H, m), 7.82–7.84 (2H, m); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.3 (CH_3), 34.5 (CH_2), 51.2 (CH_3), 63.1 (CH), 110.7 (Cq), 116.0 (CH_2), 127.1 (CH), 129.3 (CH), 133.2 (CH), 137.3 (CH), 139.7 (Cq), 150.9 (Cq), 165.9 (Cq); HRMS (ESI) *m/z* calcd for $C_{15}H_{18}NO_4S$ $[M+H]^+$ 308.0957, found 308.0960.

Methyl 2-methyl-1-(methylsulfonyl)-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3c). Yield 96%; pale yellow oil; IR (neat) 1703, 1634, 1161, 1107 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.49–2.54 (1H, m), 2.51 (3H, s), 3.01 (3H, s), 3.07–3.15 (1H, m), 3.73 (3H, s), 4.75–4.80 (1H, m), 5.21 (1H, d, *J* = 10.4 Hz), 5.34 (1H, d, *J* = 17.2 Hz), 5.86 (1H, ddd, *J* = 7.6, 10.4 and 17.6 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8 (CH_3), 34.5 (CH_2), 42.0 (CH_3), 51.2 (CH_3), 63.2 (CH), 109.2 (Cq), 117.2 (CH_2), 136.3 (CH), 150.6 (Cq), 166.0

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(Cq); HRMS (ESI) *m/z* calcd for $C_{10}H_{15}NNaO_4S$ $[M+Na]^+$ 268.0619, found 268.0617.

Methyl 2-methyl-1-(naphthalen-2-ylsulfonyl)-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3d). Yield 86%; colorless needles (AcOEt/Hexane, mp. 71.3–73.4 ºC); IR (neat) 1703, 1634, 1351, 1161, 1107 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.41–2.45 (1H, m), 2.53 (3H, s), 2.80–2.87 (1H, m), 3.65 (3H, s), 4.80–4.85 (1H, m), 5.21 (1H, d, *J* = 10.4 Hz), 5.37 (1H, d, *J* = 16.8 Hz), 5.91 (1H, ddd, *J* = 6.8, 10.4 and 16.8 Hz), 7.62–7.69 (2H, m), 7.75–7.78 (1H, m), 7.92 (1H, d, *J* = 8.0 Hz), 7.96–7.99 (2H, m), 8.43 (1H, s); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.3 (CH_3), 34.5 (CH_2), 51.1 (CH_3), 63.2 (CH), 110.6 (Cq), 116.0 (CH_2), 121.9 (CH), 127.8 (CH), 128.0 (CH), 128.8 (CH), 129.2 (CH), 129.3 (CH), 129.7 (CH), 132.1 (Cq), 135.0 (Cq), 136.6 (Cq), 137.5 (CH), 150.9 (Cq), 165.9 (Cq); HRMS (ESI) *m/z* calcd for $C_{19}H_{20}NO_4S$ $[M+H]^+$ 358.1113, found 358.1111.

Methyl 2-methyl-1-((2-nitrophenyl)sulfonyl)-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3e). Yield 82%; yellow oil; IR (neat) 1706, 1637, 1544, 1173, 1109 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.43 (3H, t, *J* = 2.0 Hz), 2.48–2.53 (1H, m), 3.07–3.15 (1H, m), 3.70 (3H, s), 4.84–4.88 (1H, m), 5.17 (1H, d, *J* = 10.4 Hz), 5.33 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 6.8, 10.4 and 17.2 Hz), 7.70–7.79 (3H, m), 8.05–8.07 (1H, m); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.9 (CH_3), 34.2 (CH_2), 51.3 (CH_3), 64.1 (CH), 110.6 (Cq), 116.2 (CH_2), 124.8 (CH), 131.0 (CH), 132.0 (CH), 133.6 (Cq), 134.3 (CH), 136.7 (CH), 148.2 (Cq), 149.7 (Cq), 165.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{15}H_{16}N_2NaO_6S$ $[M+Na]^+$ 375.0627, found 375.0623.

Methyl 2-methyl-1-((4-nitrophenyl)sulfonyl)-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3f). Yield 74%; yellow plates (AcOEt, mp. 104.8–105.9 ºC); IR (neat) 1735, 1704, 1532, 1171, 1107 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.44–2.49 (1H, m), 2.49 (3H, t, *J* = 1.6 Hz), 2.84–2.92 (1H, m), 3.69 (3H, s), 4.76–4.81 (1H, m), 5.22 (1H, d, *J* = 10.4 Hz), 5.35 (1H, d, *J* = 17.2 Hz), 5.84 (1H, ddd, *J* = 6.8, 10.0 and 16.8 Hz), 8.02 (2H, d, *J* = 8.8 Hz), 8.38 (2H, d, *J* = 8.8 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.2 (CH_3), 34.5 (CH_2), 51.4 (CH_3), 63.4 (CH), 111.8 (Cq), 116.8 (CH_2), 124.6 (CH), 128.5 (CH), 136.7 (CH), 145.4 (Cq), 149.7 (Cq), 150.3 (Cq), 165.5 (Cq); HRMS (ESI) *m/z* calcd for $C_{15}H_{16}N_2NaO_6S$ $[M+Na]^+$ 375.0627, found 375.0631.

Methyl 1-(mesitylsulfonyl)-2-methyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3g). Yield 99%; colorless needles (AcOEt/Hexane, mp. 51.9–53.2 ºC); IR (neat) 1700, 1627, 1159, 1110 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.24 (3H, t, *J* = 1.8 Hz), 2.31 (3H, s), 2.46–2.51 (1H, m), 2.61 (6H, s), 2.99–3.07 (1H, m), 3.68 (3H, s), 4.74–4.79 (1H, m), 5.10 (1H, d, *J* = 10.0 Hz), 5.25 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 6.8, 10.4 and 17.2 Hz), 6.96 (2H, s); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.1 (CH_3), 21.0 (CH_3), 22.5 (CH_3), 34.2 (CH_2), 51.0 (CH_3), 63.5 (CH), 107.1 (Cq), 115.8 (CH_2), 132.3 (CH), 134.4 (Cq), 136.8 (CH), 139.8 (Cq×2), 143.4 (Cq), 151.9 (Cq), 166.3 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{23}NNaO_4S$ $[M+Na]^+$ 372.1245, found 372.1243.

Isopropyl 2-methyl-1-tosyl-5-vinyl-4,5-dihydro-1H-pyrrole-3-carboxylate (3h). Yield 92%; colorless plates (AcOEt, mp. 72.7–74.2 ºC); IR (neat) 1698, 1635, 1168, 1092 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.22 (6H, t, *J* = 5.8 Hz), 2.38–2.45 (1H, m), 2.43 (3H, s), 2.46 (3H, S), 2.80–2.87 (1H, m), 4.69–4.74 (1H, m), 5.01 (1H, septet, *J* = 5.8 Hz), 5.18 (1H, d, *J* = 10.4 Hz), 5.33 (1H, d, *J* = 17.2 Hz), 5.89 (1H, ddd, *J* = 6.8, 9.6 and 16.4 Hz) 7.31 (2H, d, *J* = 8.4 Hz), 7.71 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.2 (CH_3), 21.6 (CH_3), 22.0 (CH_3), 34.6 (CH_2), 62.9 (CH), 67.3 (CH), 110.0 (Cq), 115.8 (CH_2), 127.2 (CH), 129.9 (CH), 136.8 (Cq), 137.6 (CH), 144.1 (Cq), 150.3 (Cq), 165.2 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{23}NO_4S$ $[M+]^+$ 349.1348, found 349.1347.

Methyl 2-propyl-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3i). Yield 90%; colorless needles (AcOEt, mp. 57.0–58.6 ºC); IR (neat) 1709, 1628, 1168, 1114 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.94 (3H, t, *J* = 7.2 Hz), 1.51–1.60 (1H, m), 1.65–1.74 (1H, m), 2.35 (1H, dd, *J* = 2.8 and 15.6 Hz), 2.43 (3H, s), 2.67–2.79 (2H, m), 3.20–3.27 (1H, m), 3.67 (3H, s), 4.65–4.70 (1H, m), 5.18 (1H, dt, *J* = 1.2 and 10.4 Hz), 5.35 (1H, dt, *J* = 1.2 and 16.8 Hz), 5.86 (1H, ddd, *J* = 6.0, 10.4 and 16.4 Hz), 7.31 (2H, d, *J* = 8.4 Hz), 7.68 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8 (CH_3), 21.5 (CH_3), 22.2 (CH_2), 29.1 (CH_2), 34.3 (CH_2), 51.1 (CH_3), 62.5 (CH), 111.8 (Cq), 115.5 (CH_2), 126.9 (CH), 129.9 (CH), 136.4 (Cq), 137.5 (CH), 144.1 (Cq), 155.6 (Cq), 165.7 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{23}NO_4S$ $[M]^+$ 349.1348, found 349.1346.

Methyl 2-isopropyl-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3j). Yield 36%; colorless needles (AcOEt/Hexane, mp. 48.8–50.3 ºC); IR (neat) 1715, 1615, 1167, 1105 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.24 (3H, d, *J* = 7.2 Hz), 1.30 (3H, d, *J* = 7.2 Hz), 2.28 (1H, dd, *J* = 1.8 and 15.8 Hz), 2.44 (3H, s), 2.61 (1H, dd, *J* = 9.8 and 15.8 Hz), 3.58 (1H, septet, *J* = 7.20 Hz), 3.68 (3H, s), 4.71–7.47 (1H, m), 5.17 (1H, d, *J* = 10.4 Hz), 5.38 (1H, d, *J* = 17.2 Hz), 5.80 (1H, ddd, *J* = 5.6, 10.4 and 16.4 Hz), 7.32 (2H, d, *J* = 8.6 Hz), 7.72 (2H, d, *J* = 8.6 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 18.2 (CH_3), 19.9 (CH_3), 21.5 (CH_3), 28.2 (CH), 34.9 (CH_2), 51.2 (CH_3), 62.8 (CH), 112.9 (Cq), 115.7 (CH_2), 127.1 (CH), 129.8 (CH), 136.9 (Cq), 136.9 (CH), 144.1 (Cq), 160.3 (Cq), 165.3 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{23}NNaO_4S$ $[M+Na]^+$ 372.1245, found 372.1248.

Methyl 2-phenyl-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3k). Yield 99%; colorless oil; IR (neat) 1717, 1697, 1171, 1189 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.42 (3H, s), 2.53 (1H, dd, *J* = 2.6 and 16.2 Hz), 2.95 (1H, dd, *J* = 10.4 and 16.2 Hz), 3.50 (3H, s), 4.96–4.99 (1H, m), 5.28 (1H, d, *J* = 10.0 Hz), 5.51 (1H, d, *J* = 17.2 Hz), 5.99 (1H, ddd, *J* = 6.0, 10.0 and 16.8 Hz), 7.21 (2H, d, *J* = 8.2 Hz), 7.28–7.33 (4H, m), 7.36–7.41 (1H, m), 7.40 (2H, d, *J* = 8.2 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 35.4 (CH_2), 51.1 (CH_3), 62.5 (CH), 113.7 (Cq), 115.8 (CH_2), 127.1 (CH), 127.4 (CH), 129.5 (CH), 129.5 (CH), 130.1 (CH), 130.6 (Cq), 136.2 (Cq), 137.3 (CH), 144.0 (Cq), 151.0 (Cq), 165.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{21}H_{21}NO_4S$ $[M]^+$ 383.1191, found 383.1189.

Methyl 2-(p-tolyl)-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3l). Yield 96%; colorless needles (AcOEt/Hexane, mp. 90.0–91.2 ºC); IR (neat) 1717, 1626, 1171, 1090 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.38 (3H, s), 2.41 (3H, s), 2.50 (1H, dd, *J* = 2.4 and 16.2 Hz), 2.88 (1H, dd, *J* = 10.0 and 16.2 Hz), 3.51 (3H, s), 4.90–4.94 (1H, m), 5.26 (1H, d, *J* = 10.0 Hz), 5.51 (1H, d, *J* = 16.8 Hz), 5.97 (1H, ddd, *J* = 6.0, 10.8 and 16.8 Hz), 7.13 (2H, d, *J* = 8.2Hz), 7.20 (2H, d, 3.2 Hz), 7.22 (2H, d, *J* = 3.2 Hz), 7.43 (2H, d, *J* = 8.2 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3×2), 35.3 (CH_2), 51.1 (CH_3), 62.3 (CH), 113.3 (Cq), 115.7 (CH_2), 127.4 (CH), 127.5 (Cq), 127.9 (CH), 129.5 (CH), 130.0 (CH), 136.1 (Cq), 137.3 (CH),

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139.7 (Cq), 144.0 (Cq), 151.3 (Cq), 165.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{22}H_{23}NNaO_4S$ $[M+Na]^+$ 420.1245, found 420.1247.

Methyl 2-(4-fluorophenyl)-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3m). Yield 98%; colorless plates (AcOEt, mp. 110.2–111.4 ºC); IR (neat) 1716, 1628, 1171, 1090 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.43 (3H, s), 2.54 (1H, dd, *J* = 2.4 and 16.4 Hz), 2.94 (1H, dd, *J* = 10.2 and 16.4 Hz), 3.52 (3H, s), 4.95–4.99 (1H, m), 5.28 (1H, d, *J* = 10.4 Hz), 5.50 (1H, d, *J* = 17.2 Hz), 5.98 (1H, ddd, *J* = 6.0, 10.4 and 16.4 Hz), 6.98–7.03 (2H, m), 7.22–7.29 (4H, m), 7.40–7.42 (2H, m); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 35.3 (CH_2), 51.2 (CH_3), 62.4 (CH), 113.9 (Cq), 114.3 (CH, d, *J* = 22.4 Hz), 115.9 (CH_2), 126.5 (Cq), 127.4 (CH), 129.6 (CH), 132.2 (CH, d, *J* = 9.1 Hz), 136.2 (Cq), 137.3 (CH), 144.2 (Cq), 150.0 (Cq), 163.4 (Cq, d, *J* = 247.8 Hz), 164.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{21}H_{21}NO_4FS$ $[M+H]^+$ 402.1175, found 402.1171.

Methyl 2-(4-methoxyphenyl)-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrole-3-carboxylate (3n). Yield 93%; colorless needles (AcOEt/Hexane, mp. 117.6–119.0 ºC); IR (neat) 1715, 1606, 1171, 1089 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.42 (3H, s), 2.50 (1H, dd, *J* = 2.6 and 16.0 Hz), 2.87 (1H, dd, *J* = 10.0 and 16.0 Hz), 3.52 (3H, s), 3.85 (3H, s), 4.91–4.95 (1H, m), 5.27 (1H, dt, *J* = 1.2 and 10.4 Hz), 5.51 (1H, dt, *J* = 1.2 and 16.8 Hz), 5.97 (1H, ddd, *J* = 5.6, 10.4 and 16.0 Hz), 6.84 (2H, d, *J* = 8.6 Hz), 7.22–7.30 (4H, m), 7.43 (2H, d, *J* = 8.6 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 35.3 (CH_2), 51.1 (CH_3), 55.2 (CH_3), 62.3 (CH), 112.6 (CH), 112.9 (Cq), 115.7 (CH_2), 122.6 (Cq), 127.5 (CH), 129.5 (CH), 131.8 (CH), 136.3 (Cq), 137.4 (CH), 144.0 (Cq), 151.1 (Cq), 160.8 (Cq), 165.2 (Cq); HRMS (ESI) *m/z* calcd for $C_{22}H_{23}NO_5S$ $[M]^+$ 413.1297, found 413.1301.

1-(2-Methyl-1-tosyl-5-vinyl-4,5-dihydro-1*H*-pyrrol-3-yl)ethanone (3o). Yield 91%; pale yellow needles (AcOEt, mp. 95.6–97.1 ºC); IR (neat) 1671, 1595, 1168, 1093 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.14 (3H, s), 2.44 (3H, s), 2.46 (3H, s), 2.44–2.48 (1H, m), 2.91–3.01 (1H, m), 4.77–7.82 (1H, m), 5.20 (1H, d, *J* = 10.4 Hz), 5.34 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 6.8, 10.4 and 17.2 Hz), 7.31 (2H, *J* = 8.4 Hz), 7.71 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.6 (CH_3), 21.5 (CH_3), 30.1 (CH_3), 35.5 (CH_2), 63.1 (CH), 116.2 (CH_2), 118.3 (Cq), 127.2 (CH), 129.9 (CH), 136.8 (Cq), 137.3 (CH), 144.3 (Cq), 150.1 (Cq), 195.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{16}H_{19}NNaO_3S$ $[M+Na]^+$ 328.0983, found 328.0979.

1-Tosyl-2-vinyl-2,3,6,7-tetrahydro-1H-indol-4(5*H*)-one (3p). Yield 89%; pale yellow oil; IR (neat) 1654, 1620, 1395, 1361, 1166 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.03 (2H, quint., *J* = 6.4 Hz), 2.33 (2H, t, *J* = 6.4 Hz), 2.41–2.45 (1H, m), 2.45 (3H, s), 2.68–2.76 (1H, m), 2.79–2.89 (2H, m), 4.73–4.78 (1H, m), 5.19 (1H, d, *J* = 10.4 Hz), 5.32 (1H, d, *J* = 17.2 Hz), 5.85 (1H, ddd, *J* = 6.8, 10.0 and 16.8 Hz), 7.34 (2H, d, *J* = 8.2 Hz), 7.71 (2H, d, *J* = 8.2 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 22.6 (CH_2), 24.7 (CH_2), 31.6 (CH_2), 36.4 (CH_2), 64.7 (CH), 116.4 (CH_2), 119.4 (Cq), 127.1 (CH), 130.0 (CH), 136.2 (Cq), 137.0 (CH), 144.6 (Cq), 158.8 (Cq), 195.7 (Cq); HRMS (ESI) *m/z* calcd for $C_{17}H_{19}NNaO_3S$ $[M+Na]^+$ 340.0983, found 340.0987.

(3a*S,7a*S**)-Methyl 2-methyl-1-tosyl-3a,4,5,7a-tetrahydro-1*H*-indole-3-carboxylate (3q).** Yield 81%; colorless plates (AcOEt, mp. 112.2–113.9 ºC); IR (neat) 1701, 1626, 1169, 1106 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.63–1.72 (1H, m), 1.79–1.91 (2H, m), 1.96–2.04 (1H, m), 2.43 (3H, s), 2.44 (3H, s), 3.00–3.06 (1H, m), 3.70 (3H, s), 4.47 (1H, dd, *J* = 2.2 and 9.0 Hz), 6.01–6.10 (2H, m), 7.31 (2H, d, *J* = 8.6 Hz), 7.70 (2H, d, *J* = 8.6 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.6 (CH_3), 21.5 (CH_3), 22.2 (CH_2), 23.8 (CH_2), 39.5 (CH), 51.0 (CH_3), 60.2 (CH), 114.9 (Cq), 125.2 (CH), 127.1 (CH), 129.9 (CH), 132.7 (CH), 136.5 (Cq), 144.1 (Cq), 151.9 (Cq), 166.1 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{21}NO_4S$ $[M]^+$ 347.1191, found 347.1194.

General procedure for the synthesis of 3-methylene-1,2,3,4-tetrahydropyridines 5 (Scheme 6)

To a stirred solution of β-enamino ester **1a** (53.9 mg, 200 μmol) in dioxane (2.0 mL) were added 2-methylenepropane-1,3-diyl diacetate (**4**) (41.3 mg, 240 μmol), $Pd(OAc)_2$ (4.5 mg, 20.0 μmol), (±)-BINAP (24.9 mg, 40.0 μmol) and K_2CO_3 (111 mg, 800 μmol) at rt, and stirring was continued for 30 min at the same temperature under argon atmosphere. The reaction mixture was then allowed to heat to 120 ºC, and further stirring was continued for 20 min. After filtration of the reaction mixture using small amount of silica gel followed by concentration, the residue was chromatographed on silica gel with AcOEt–hexane (1:6 v/v) as eluent to give the 3-methylene-1,2,3,4-tetrahydropyridine **5a** (63.1 mg, 196 μmol, 98%) as a pale yellow oil.

Methyl 2-methyl-5-methylene-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5a). Yield 98%; pale yellow oil; IR (neat) 1715, 1354, 1235, 1164, 1091 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.41 (3H, s), 2.50 (3H, t, *J* = 2.0 Hz), 2.79 (2H, d, *J* = 2.0 Hz), 3.72 (3H, s), 4.10 (2H, s), 4.73 (1H, s), 4.80 (1H, s), 7.24 (2H, d, *J* = 8.4 Hz), 7.62 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.1 (CH_3), 21.5 (CH_3), 31.4 (CH_2), 51.6 (CH_3), 52.2 (CH_2), 111.1 (CH_2), 118.0 (Cq), 127.4 (CH), 129.4 (CH), 136.6 (Cq), 137.8 (Cq), 143.9 (Cq), 147.0 (Cq), 167.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{16}H_{19}NO_4S$ $[M]^+$ 321.1035, found 321.1036.

Isopropyl 2-methyl-5-methylene-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5h). Yield 99%; colorless plates (AcOEt, mp. 95.0–96.1 ºC); IR (neat) 1706, 1355, 1165 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.27 (6H, d, *J* = 9.6 Hz), 2.41 (3H, s), 2.47 (3H, t, *J* = 2.0 Hz), 2.76 (2H, d, *J* = 2.0 Hz), 4.09 (2H, s), 4.73 (1H, s), 4.79 (1H, s), 5.05 (1H, septet., *J* = 2.4 Hz), 7.24 (2H, d, *J* = 8.0 Hz), 7.62 (2H, d, *J* = 8.0 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.1 (CH_3), 21.5 (CH_3), 21.9 (CH_3), 31.5 (CH_2), 52.2 (CH_2), 68.0 (CH), 111.0 (CH_2), 118.9 (Cq), 127.4 (CH), 129.4 (CH), 136.7 (Cq), 138.0 (Cq), 143.8 (Cq), 145.8 (Cq), 167.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{23}NO_4S$ $[M]^+$ 349.1348, found 349.1351.

Methyl 5-methylene-2-propyl-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5i). Yield 94%; colorless plates (AcOEt, mp. 85.4–86.1 ºC); IR (neat) 1710, 1351, 1239, 1090 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.90 (3H, t, *J* = 7.4 Hz), 1.58 (2H, sextet, *J* = 7.4 Hz), 2.41 (3H, s), 2.69 (2H, s), 2.95 (2H, t, *J* = 7.4 Hz), 3.72 (3H, s), 4.07 (2H, s), 4.70 (1H, s), 4.81 (1H, s), 7.23 (2H, d, *J* = 8.6 Hz), 7.62 (2H, d, *J* = 8.6 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.9 (CH_3), 21.5 (CH_3), 21.9 (CH_2), 31.2 (CH_2), 34.9 (CH_2), 51.7 (CH_3), 52.7 (CH_2), 110.9 (CH_2), 120.4 (Cq), 127.5 (CH), 129.4 (CH), 136.5 (Cq),

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138.6 (Cq), 143.8 (Cq), 151.0 (Cq), 167.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{24}NO_4S$ $[M+H]^+$ 350.1426, found 350.1424.

Methyl 2-isopropyl-5-methylene-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5j). Yield 75%; colorless plates (AcOEt, mp. 81.9–83.2 ºC); IR (neat) 1718, 1352, 1165 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.26 (6H, d, *J* = 7.2 Hz), 2.40–2.41 (2H, m), 2.46 (3H, s), 3.45 (1H, septet, *J* = 7.2 Hz), 3.74 (3H, s), 4.05 (2H, s), 4.61 (1H, s), 4.79 (1H, s), 7.23 (2H, d, *J* = 8.0 Hz), 7.64 (2H, d, *J* = 8.0 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 20.0 (CH_3), 21.5 (CH_3), 31.3 (CH_2), 33.6 (CH), 51.8 (CH_3), 53.3 (CH_2), 110.4 (CH_2), 124.7 (Cq), 127.8 (CH), 129.3 (CH), 136.3 (Cq), 139.7 (Cq), 143.8 (Cq), 152.1 (Cq), 168.5 (Cq); HRMS (ESI) *m/z* calcd for $C_{18}H_{23}NNaO_4S$ $[M+Na]^+$ 372.1245, found 372.1246.

Methyl 5-methylene-2-phenyl-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5k). Yield 99%; colorless plates (AcOEt, mp. 110.7–111.1 ºC); IR (neat) 1707, 1360, 1168 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.40 (3H, s), 2.96 (2H, s), 3.40 (3H, s), 4.30 (2H, s), 4.85 (1H, s), 4.93 (1H, s), 7.16 (2H, d, *J* = 8.2 Hz), 7.23–7.35 (5H, m), 7.39 (2H, d, *J* = 8.2 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 31.8 (CH_2), 51.5 (CH_3), 52.7 (CH_2), 112.0 (CH_2), 120.5 (Cq), 127.5 (CH), 127.6 (CH), 129.0 (CH), 129.1 (CH), 129.2 (CH), 136.5 (Cq), 136.6 (Cq), 137.8 (Cq), 143.7 (Cq), 146.0 (Cq), 168.8 (Cq); HRMS (ESI) *m/z* calcd for $C_{21}H_{21}NNaO_4S$ $[M+Na]^+$ 406.1089, found 406.1092.

Methyl 5-methylene-2-(p-tolyl)-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5l). Yield 95%; colorless needles (AcOEt, mp. 94.8–96.0 ºC); IR (neat) 1707, 1360, 1168 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.36 (3H, s), 2.40 (3H, s), 2.92 (2H, s), 3.44 (3H, s), 4.28 (2H, s), 4.83 (1H, s), 4.92 (1H, s), 7.08 (2H, d, *J* = 8.2 Hz), 7.14 (2H, d, *J* = 8.4 Hz), 7.16 (2H, d, *J* = 8.4 Hz), 7.40 (2H, d, *J* = 8.2 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.4 (CH_3), 21.5 (CH_3), 31.7 (CH_2), 51.5 (CH_3), 52.7 (CH_2), 111.8 (CH_2), 120.0 (Cq), 127.7 (CH), 128.3 (CH), 129.1 (CH), 129.1 (CH), 133.7 (Cq), 136.5 (Cq), 138.1 (Cq), 139.0 (Cq), 143.7 (Cq), 146.2 (Cq), 169.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{22}H_{23}NO_4S$ $[M]^+$ 397.1348, found 397.1350.

Methyl 2-(4-fluorophenyl)-5-methylene-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5m). Yield 94%.; colorless needles (AcOEt/Hexane, mp. 87.0–88.7 ºC); IR (neat) 1716, 1507, 1361, 1168 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.41 (3H, s), 2.97 (2H, s), 3.44 (3H, s), 4.29 (2H, s), 4.87 (1H, s), 4.95 (1H, s), 6.93–6.98 (2H, m), 7.17–7.22 (4H, m), 7.38 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 31.8 (CH_2), 51.6 (CH_3), 52.6 (CH_2), 112.1 (CH_2), 114.6 (CH, d, *J* = 21.7 Hz), 120.3 (Cq), 127.6 (CH), 129.3 (CH), 131.0 (CH, d, *J* = 8.3 Hz), 132.5 (Cq), 136.6 (Cq), 137.7 (Cq), 143.9 (Cq), 145.1 (Cq), 163.1 (Cq, d, *J* = 247.0 Hz), 168.6 (Cq); HRMS (ESI) *m/z* calcd for $C_{21}H_{20}NO_4FNaS$ $[M+Na]^+$ 424.0995, found 424.0998.

Methyl 2-(4-methoxyphenyl)-5-methylene-1-tosyl-1,4,5,6-tetrahydropyridine-3-carboxylate (5n). Yield 96%; colorless needles (AcOEt, mp. 135.9–138.3 ºC); IR (neat) 1704, 1358, 1251, 1168 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.40 (3H, s), 2.93 (2H, s), 3.44 (3H, s), 3.82 (3H, s), 4.29 (2H, s), 4.85 (1H, s), 4.94 (1H, s), 6.79 (2H, d, *J* = 8.8 Hz), 7.17 (4H, d, *J* = 8.8 Hz), 7.39 (2H, d, *J* = 8.0 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 31.7 (CH_2), 51.5 (CH_3), 52.7 (CH_2), 55.1 (CH_3), 111.8 (CH_2), 113.0 (CH), 119.3 (Cq), 127.7 (CH), 128.8 (Cq), 129.1 (CH), 130.6 (CH), 136.6 (Cq), 138.2 (Cq), 143.7 (Cq), 146.0 (Cq), 160.3 (Cq), 169.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{22}H_{23}NNaO_5S$ $[M+Na]^+$ 436.1195, found 436.1194.

1-(2-Methyl-5-methylene-1-tosyl-1,4,5,6-tetrahydropyridin-3-yl)ethanone (5o). Yield 87%; pale yellow oil; IR (neat) 1684, 1351, 1163 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.23 (3H, s), 2.36 (3H, t, *J* = 2.0 Hz), 2.42 (3H, s), 2.74 (2H, d, *J* = 2.0 Hz), 4.11 (2H, s), 4.77 (1H, s), 4.85 (1H, s), 7.25 (2H, d, *J* = 8.8 Hz), 7.62 (2H, d, *J* = 8.8 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 20.9 (CH_3), 21.5 (CH_3), 30.0 (CH_3), 31.7 (CH_2), 52.0 (CH_2), 111.3 (CH_2), 126.9 (Cq), 127.3 (CH), 129.4 (CH), 136.6 (Cq), 137.6 (Cq), 142.7 (Cq), 143.9 (Cq), 201.0 (Cq); HRMS (ESI) *m/z* calcd for $C_{16}H_{19}NO_3S$ $[M]^+$ 305.1086, found 305.1087.

3-Methylene-1-tosyl-1,2,3,4,7,8-hexahydroquinolin-5(6*H*)-one (5p). Yield 91%; colorless plates (AcOEt, mp. 127.3–129.5 ºC); IR (neat) 1659, 1361, 1164 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.90–1.96 (2H, m), 2.37–2.42 (5H, m), 2.85–2.88 (4H, m), 4.17 (2H, s), 4.87 (2H, s), 7.27 (2H, d, *J* = 8.2 Hz), 7.62 (2H, d, *J* = 8.2 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 22.1 (CH_2), 28.4 (CH_2), 29.7 (CH_2), 37.0 (CH_2), 52.6 (CH_2), 112.3 (CH_2), 122.0 (Cq), 127.1 (CH), 129.8 (CH), 136.5 (Cq), 144.4 (Cq), 154.2 (Cq), 197.6 (Cq); HRMS (ESI) *m/z* calcd for $C_{17}H_{19}NNaO_3S$ $[M+Na]^+$ 340.0983, found 340.0983.

Acknowledgements

This study was supported in part by a Grant-in-Aid for Scientific Technique Research Promotion Program for Agriculture, Forestry, Fisheries and Food Industry from the Ministry of Agriculture, Forestry and Fisheries.

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† Electronic Supplementary Information (ESI) available: Copies of ^{1}H and ^{13}C NMR spectra for all new compounds. See DOI: 10.1039/b000000x/

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11 We also examined the reactivity of benzyl- and Boc-substituted β-enamino esters, but no reactions proceeded in these cases.

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