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SYNTHESES OF 2-VINYL-2,3-DIHYDROPYRROLES AND 3-METHYLENE-1,2,3,4-TETRAHYDROPYRIDINES BY PALLADIUM-CATALYZED CYCLIZATION OF *N*-TOSYL IMINES WITH ALLYLIC DIESTERS

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Abstract – A palladium-catalyzed cyclization of *N*-tosyl imines with allylic diesters is described. The reactions of *N*-tosyl imines with 2-buten-1,4-diol dicarbonate and 2-methylene-1,3-propanediol diacetate afforded 2-vinyl-2,3-dihydropyrroles and 3-methylene-1,2,3,4-tetrahydropyridines, respectively.

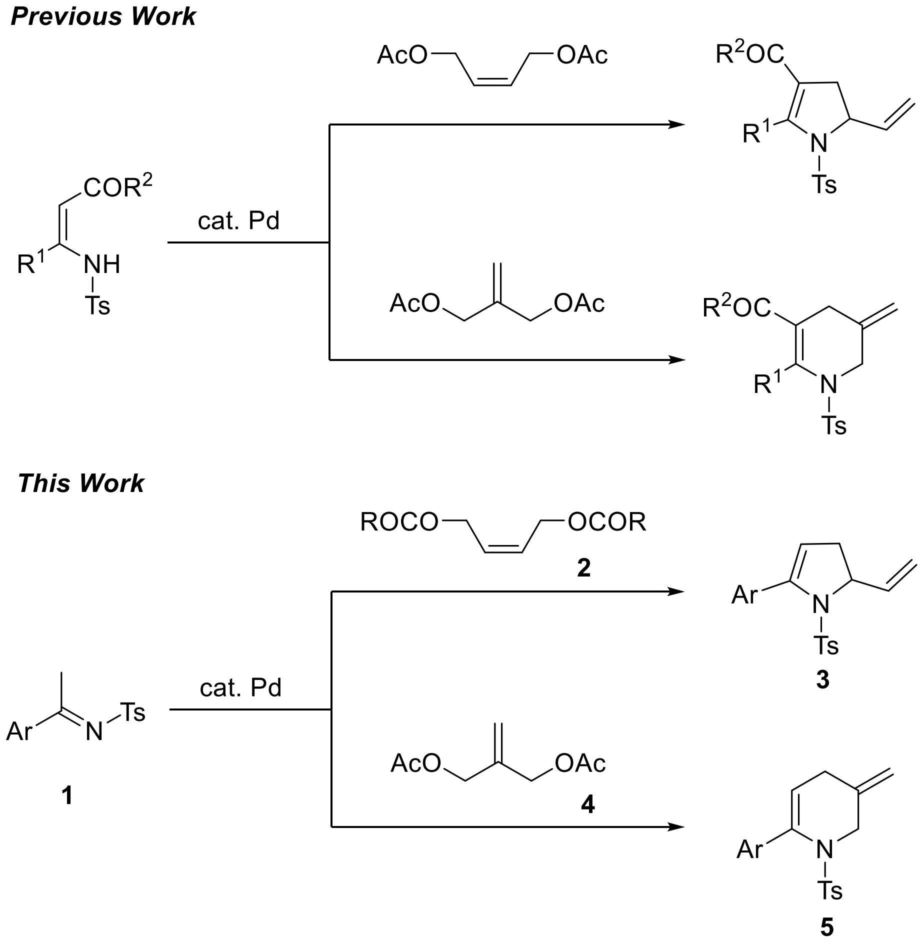
INRODUCTION

Substituted dihydropyrroles and tetrahydropyridines are an important class of heteroaromatic compounds, and these are components as a structural fragment of biologically active natural products and pharmaceutical agents.[1,2] From this reason, constructive effort has been devoted toward developing a methodology for the syntheses of substituted dihydropyrroles and tetrahydropyridines.[3,4]

Palladium-catalyzed reactions of allylic diesters with bis-nucleophiles have received considerable attention and have been extensively studied.[5–7] In these reactions, a substrate having two nucleophilic moieties within the molecule successively reacted with allylic diesters to afford the cyclized product. A variety of cyclic compounds can be synthesized in one-step by the choice of adequately designed nucleophilic molecules. For example, we have recently reported syntheses of functionalized dihydropyrroles and tetrahydropyridines by palladium-catalyzed cyclizations of β-enaminocarbonyl compounds with allylic diacetates (Scheme 1).[7c] In these reactions, β-enaminocarbonyl compounds react

‡ This paper is dedicated to Professor Dr. Masakatsu Shibasaki on the occasion of his 70th birthday.

with 1,4-diacyloxy-2-butene and 2-methylene-1,3-propanediol diacetate to afford substituted dihydropyrroles and tetrahydropyridines via successive double allylic substitutions, respectively. During the course of our planning for further investigation of this cyclization, we took notice of the nucleophilic activity of *N*-tosyl imines **1**, which does not have electron-withdrawing carbonyl moiety. Herein, we describe a palladium-catalyzed cyclization of *N*-tosyl imines **1** with allylic diesters **2** and **4**, in which the substituted dihydropyrroles **3** and tetrahydropyridines **5** were produced in one-step, respectively.

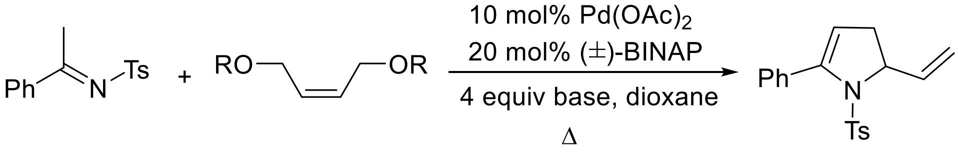


Scheme 1

RESULTS AND DISCUSSION

The examinations were started using phenyl-substituted *N*-tosyl imine **1a** and (*Z*)-1,4-diacetoxy-2-butene (**2a**) (Table 1). When **1a** and **2a** were treated with 10 mol% $Pd(OAc)_2$, 20 mol% (±)-BINAP and 4 equiv K_2CO_3 in dioxane at 120 °C according to our previous condition,[7c] the expected 2-vinyl-2,3-dihydropyrrole **3a** was produced in 63% yield (entry 1). The reactions in the presence of various base such as K_3PO_4, Cs_2CO_3, NaOH and ^{i}Pr$_2$NEt resulted in the production of **3a** in low yields, respectively (entries 2–5).[8] Experimenting using allylic dicarbonates **2b–2d** in the absence of base (entries 6–8) revealed that **3a** was obtained in 62% yield in the case of benzyl carbonate **2d** (entry 8). After attempts under various reaction temperature (entries 9 and 10), we found that the yield was increased to 70% when the reaction was carried out at 80 ºC (entry 9).

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



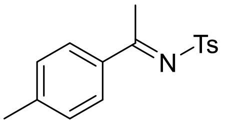
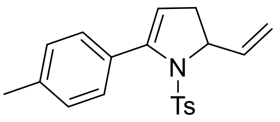
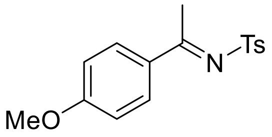
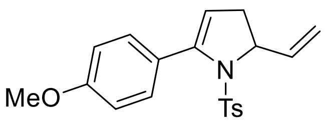
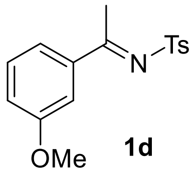
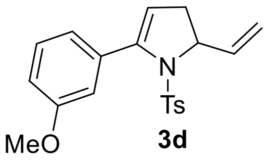
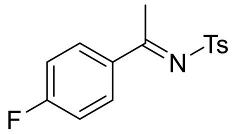
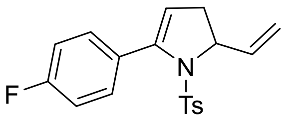
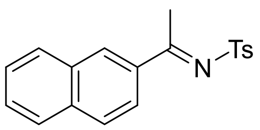
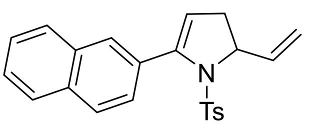
1a **2a–2d** **3a**

Entry	R	Base	Temp (ºC)	Yield (%)
1	Ac (**2a**)	K_2CO_3	120	63
2	Ac (**2a**)	K_3PO_4	120	58
3	Ac (**2a**)	Cs_2CO_3	120	47
4	Ac (**2a**)	NaOH	120	41
5	Ac (**2a**)	^{i}Pr$_2$NEt	120	35
6	CO_2Me (**2b**)	–	120	57
7	$CO_2{}^t$Bu (**2c**)	–	120	41
8	CO_2Bn (**2d**)	–	120	62
9	CO_2Bn (**2d**)	–	80	70
10	CO_2Bn (**2d**)	–	50	49

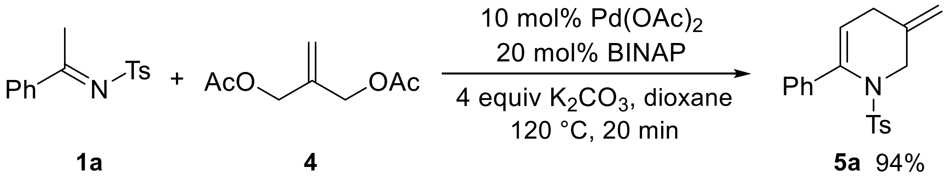
Having identified a useful set of reaction conditions, we carried out a study using various aryl-substituted *N*-tosyl imines **1b–1f** with **2d** (Table 2). When a substrate **1b** having a tolyl group was exposed to the optimal conditions, the dihydropyrrole **3b** was obtained in 60% yield (entry 1). Methoxy- and fluoro-substituted substrates **1c–1e** reacted without problems to afford the corresponding products **3c–3e** in moderate yields, respectively (entries 2–4). The reaction of **1f** which contains naphthyl group also proceeded to give the cyclized product **3f** in 66% yield (entry 5).

We next conducted the reactions using 2-methylene-1,3-propanediol diacetate (**4**). When *N*-tosyl imine **1a** and **4** were subjected to the reaction with 10 mol% $Pd(OAc)_2$, 20 mol% (±)-BINAP and 4 equiv K_2CO_3 in dioxane at 120 °C,[7c] the reaction successfully proceeded to produce the 3-methylene-1,2,3,4-tetrahydropyridine **5a** in 94% yield (Scheme 2).

Table 2. Reactions using various aryl-substituted *N*-tosyl imines **1b–1f** with **2d**

Entry	Substrate **1**	Product **3**	Yield (%)
1	 **1b**	 **3b**	60
2	 **1c**	 **3c**	56
3	 **1d**	 **3d**	46
4	 **1e**	 **3e**	54
5	 **1f**	 **3f**	66

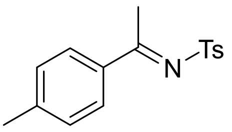
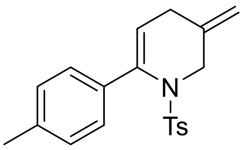
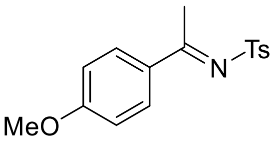
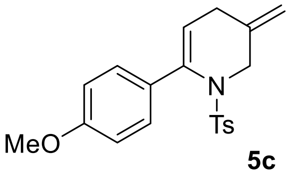
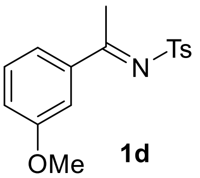
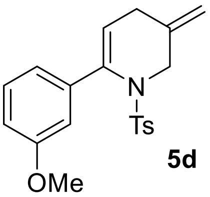
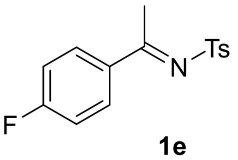
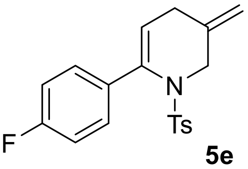
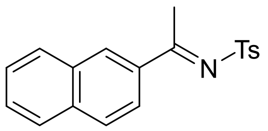
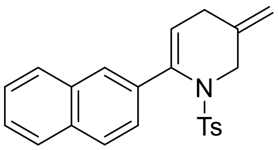
[a] Reactions were carried out with **2c** in the presence of 10 mol% Pd(OAc)$_2$, 20 mol% (±)-BINAP in dioxane at 80 ºC.



Scheme 2

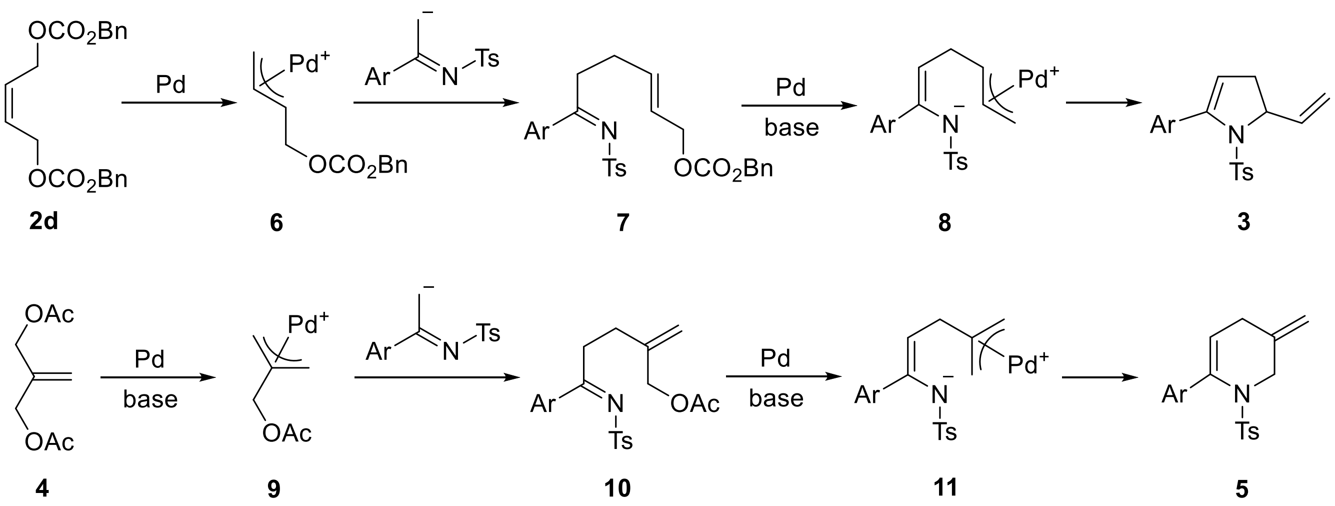
Table 3 summarized the examinations using *N*-tosyl imines **1b**–**1f**. The reactions of allylic diacetate **4** with tolyl-substituted *N*-tosyl imines **1b** afforded the tetrahydropyridine **5b** in 93% yield (entry 1). Similarly, substrates **1c**–**1f** having various aryl group also reacted to give the corresponding products **5c**–**5f** in good yields, respectively (entries 2–5).

Table 3. Reactions using various *N*-tosyl arylimines **1b–1f** with **4**

Entry	Substrate **1**	Product **5**	Yield (%)
1	 **1b**	 **5b**	93
2	 **1c**	 **5c**	91
3	 **1d**	 **5d**	87
4	 **1e**	 **5e**	91
5	 **1f**	 **5f**	92

[a] 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 at 120 °C.

A plausible mechanisms for the production of dihydropyrrole **3** and tetrahydropyridine **5** are shown in Scheme 3. By the reaction with palladium, 2-butene-1,4-diol dicarbonate **2d** is transformed to the π-allylpalladium complex **6**, which causes the nucleophilic attack of the *N*-tosyl imine anion to afford the substituted allylic carbonate **7**. The compound **7** is further subjected to the intramolecular nucleophilic attack of the tosyl amide anion via the formation of π-allylpalladium intermediate **8** to produce the 2,3-dihydropyrrole **3**. 2-Methylene-1,3-propanediol diacetate **4** is also converted to the corresponding π-allylpalladium complex **9**, which is subjected to the nucleophilic attack of the *N*-tosyl imine anion to afford allylic acetate **10**. Then intramolecular nucleophilic cyclization of **10** occurs via the π-allylpalladium intermediate **11** to produce the tetrahydropyridine **5**. In these reactions, it is interesting that *N*-tosyl imines which does not have electron-withdrawing carbonyl group act as a bis-nucleophile in mild reaction conditions.



Scheme 3

CONCLUSIONS

In conclusion, the studies described above have resulted in the synthesis of functionalized dihydropyrroles and tetrahydropyridines by the palladium-catalyzed cyclization of *N*-tosyl imines with allylic diesters. In this reaction, *N*-tosyl imines which does not have electron-withdrawing carbonyl moiety act as bis-nucleophile in mild reaction conditions. Since many biologically active molecules containing a pyrrolidine and piperidine component have been reported, our methodology could provide a new protocol for the syntheses of these compounds.

EXPERIMENTAL

All 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 the standard protocols. *N*-tosyl imines **1** and allylic disesters **2** and **4** were prepared according to the procedures described in the literature.[9,10,11]

General Procedure for the Synthesis of Dihydropyrrole

Synthesis of 3a (entry 9 in Table 1): To a stirred solution of *N*-tosyl imine **1a** (20.0 mg, 73.2 μmol) in dioxane (0.7 mL) were added allylic dicarbonate **2d** (26.1 mg, 73.2 μmol), $Pd(OAc)_2$ (1.6 mg, 7.3 μmol), and (±)-BINAP (9.1 mg, 14.6 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 80 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 (1:8 v/v) as eluent to give **3a** (16.7 mg, 51.2 μmol, 70%) as pale yellow needles.

5-Phenyl-1-tosyl-2-vinyl-2,3-dihydro-1*H*-pyrrole (3a)

Yield 70%; pale yellow needles (AcOEt/hexane, mp 90.4–91.3 ºC); IR (neat) 1352, 1167, 755, 666 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.00–2.05 (1H, m), 2.11–2.17 (1H, m), 2.43 (3H, s), 4.78–4.81(1H, m), 5.19 (1H, d, *J* = 10.4 Hz), 5.39 (1H, dd, *J* = 2.0 and 3.6 Hz), 5.54 (1H, d, *J* = 16.8 Hz), 5.88 (1H, ddd, *J* = 4.8, 10.4 and 16.8 Hz), 7.26–7.29 (2H, m), 7.34–7.38 (3H, m), 7.57–7.59 (4H, m); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 35.3 (CH_2), 64.1 (CH), 114.9 (CH_2), 116.0 (CH), 127.5 (CH), 127.8 (CH), 127.9 (CH), 128.6 (CH), 129.4 (CH), 133.3 (Cq), 134.4 (Cq), 137.5 (CH), 143.7 (Cq), 144.1 (Cq); HRMS (ESI) *m/z* calcd for $C_{19}H_{19}NNaO_2S$ $[M+Na]^+$ 348.1034, found 348.1032.

5-(4-Methylphenyl)-1-tosyl-2-vinyl-2,3-dihydro-1*H*-pyrrole (3b)

Yield 60%; pale yellow needles (AcOEt/hexane, mp 93.5–96.0 ºC); IR (neat) 1352, 1167, 1091, 820 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.98–2.02 (1H, m), 2.07–2.14 (1H, m), 2.37 (3H, s), 2.43 (3H, s), 4.76–4.79 (1H, m), 5.18 (1H, d, *J* = 10.0 Hz), 5.33 (1H, dd, *J* = 2.0 and 3.6 Hz), 5.53 (1H, d, *J* = 16.8 Hz), 5.88 (1H, ddd, *J* = 5.2, 10.0 and 16.8 Hz), 7.17 (2H, d, *J* = 8.4 Hz), 7.27 (2H, d, *J* = 8.4 Hz), 7.48 (2H, d, *J* = 8.4 Hz), 7.58 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.3 (CH_3), 21.6 (CH_3), 34.2 (CH_2), 64.1 (CH), 114.9 (CH_2), 115.1 (CH), 127.5 (CH), 127.8 (CH), 128.6 (CH), 129.3 (CH), 130.4 (Cq), 134.5 (Cq), 137.6 (CH), 138.6 (Cq), 143.6 (Cq), 144.1 (Cq); HRMS (ESI) *m/z* calcd for $C_{20}H_{21}NNaO_2S$ $[M+Na]^+$ 362.1191, found 362.1189.

5-(4-Methoxyphenyl)-1-tosyl-2-vinyl-2,3-dihydro-1*H*-pyrrole (3c)

Yield 56%; pale red needles (AcOEt/hexane, mp 112.5–114.2 ºC); IR (neat) 1508, 1457, 1250, 1166 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.97–2.03 (1H, m), 2.08-2.14 (1H, m), 2.43 (3H, s), 3.82 (3H, s), 4.75–4.80 (1H, m), 5.18 (1H, d, *J* = 10.4 Hz), 5.27 (1H, dd, *J* = 2.0 and 3.4 Hz), 5.52 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 5.6, 10.4 and 17.2 Hz), 6.90 (2H, d, *J* = 8.8 Hz), 7.27 (2H, d, *J* = 8.8 Hz), 7.51 (2H, d, *J* = 8.8 Hz), 7.57 (2H, d, *J* = 8.8 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 34.1 (CH_2), 55.3 (CH_3), 64.1 (CH), 113.3 (CH), 114.2 (CH_2), 114.9 (CH), 125.8 (Cq), 127.8 (CH), 128.9 (CH), 129.3 (CH) 134.5 (Cq), 137.6 (CH), 143.6 (Cq), 143.7 (Cq), 159.9 (Cq); HRMS (ESI) *m/z* calcd for $C_{20}H_{22}NO_3S$ $[M+H]^+$ 356.1320, found 356.1318.

5-(3-Methoxyphenyl)-1-tosyl-2-vinyl-2,3-dihydro-1*H*-pyrrole (3d)

Yield 46%; colorless needles (AcOEt/hexane, mp 95.1–98.2 ºC); IR (neat) 1353, 1166, 1041, 668 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 1.99–2.05 (1H, m), 2.10–2.17 (1H, m), 2.43 (3H, s), 3.84 (3H, s)

4.77–4.81 (1H, m), 5.19 (1H, d, *J* = 10.4 Hz), 5.40 (1H, dd, *J* = 2.0 and 4.0 Hz), 5.52 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 5.2, 10.4 and 17.2 Hz), 6.88–6.90 (1H, m), 7.11–7.12 (1H, m), 7.16–7.18 (1H, m), 7.25–7.30 (3H, m), 7.60 (2H, d, *J* = 7.6 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 34.3 (CH_2), 55.3 (CH_3), 64.1 (CH), 113.3 (CH), 114.2 (CH), 115.0 (CH_2), 116.4 (CH), 120.1 (CH), 127.8 (CH), 128.9 (CH), 129.3 (CH), 129.6 (Cq), 134.6 (Cq), 137.5 (CH), 143.7 (Cq), 143.9 (Cq), 159.1 (Cq); HRMS (ESI) *m/z* calcd for $C_{20}H_{21}NNaO_3S$ $[M+Na]^+$ 378.1140, found 378.1136.

5-(4-Fluorophenyl)-1-tosyl-2-vinyl-2,3-dihydro-1*H*-pyrrole (3e)

Yield 54%; yellow needles (AcOEt/hexane, mp 120.5–123.7 ºC); IR (neat) 1507, 1353, 1222, 1167 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.00–2.06 (1H, m), 2.11-2.18 (1H, m), 2.44 (3H, s), 4.77–4.81 (1H, m), 5.20 (1H, d, *J* = 10.4 Hz), 5.34 (1H, dd, *J* = 2.4 and 3.6 Hz), 5.51 (1H, d, *J* = 17.2 Hz), 5.88 (1H, ddd, *J* = 5.2, 10.4 and 17.2 Hz), 7.05 (2H, t, *J* = 8.8 Hz), 7.28 (2H, d, *J* = 8.4 Hz), 7.54 (2H, t, *J* = 8.8 Hz), 7.56 (2H, d, *J* = 8.4 Hz); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 34.3 (CH_2), 64.1 (CH), 114.9 (CH, d, *J* = 21.5 Hz), 115.2 (CH_2), 115.8 (CH), 117.8 (CH), 129.3 (CH, d, *J* = 7.4 Hz), 129.4 (Cq), 129.4 (CH), 134.4 (Cq), 137.5 (CH), 143.0 (Cq), 143.8 (Cq), 162.9 (Cq, d, *J* = 247.0 Hz); HRMS (ESI) *m/z* calcd for $C_{19}H_{19}FNO_2S$ $[M+H]^+$ 344.1121, found 344.1118.

5-(Naphthalen-2-yl)-1-tosyl-2-vinyl-2,3-dihydro-1*H*-pyrrole (3f)

Yield 66%; pale orange needles (AcOEt/hexane, mp 135.3–137.0 ºC); IR (neat) 1353, 1167, 772, 667 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.05–2.11 (1H, m), 2.17–2.24 (1H, m), 2.43 (3H, s), 4.83–4.87 (1H, m), 5.23 (1H, d, *J* = 10.4 Hz), 5.52 (1H, dd, *J* = 2.0 and 3.6 Hz), 5.58 (1H, d, *J* = 16.8 Hz), 5.93 (1H, ddd, *J* = 5.6, 10.4 and 16.8 Hz), 7.27 (2H, d, *J* = 8.4 Hz), 7.46–7.51 (2H, m), 7.60 (2H, d, *J* = 8.4 Hz), 7.70–7.72 (1H, m), 7.81–7.87 (3H, m), 8.00 (1H, s); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.6 (CH_3), 34.4 (CH_2), 64.2 (CH), 115.1 (CH_2), 116.6 (CH), 125.6 (CH), 126.2 (CH), 126.3 (CH), 126.4 (CH), 127.4 (CH), 127.7 (CH), 127.8 (CH), 128.2 (CH), 129.4 (CH), 130.7 (Cq), 132.9 (Cq), 133.5 (Cq), 134.5 (Cq), 137.5 (CH), 143.8 (Cq), 144.1 (Cq); HRMS (ESI) *m/z* calcd for $C_{23}H_{21}NNaO_2S$ $[M+Na]^+$ 398.1191, found 398.1189.

General Procedure for the Synthesis of Tetrahydropyridine

Synthesis of 5a (Scheme 2): To a stirred solution of *N*-tosyl imine **1a** (27.3 mg, 100 μmol) in dioxane (1.0 mL) were added allylic diacetate **4** (34.4 mg, 200 μmol), $Pd(OAc)_2$ (2.2 mg, 10.0 μmol), (±)-BINAP (12.5 mg, 20.0 μmol), and K_2CO_3 (55.3 mg, 400 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 tetrahydropyridine **5a** (30.6 mg, 94.0 μmol, 94%) as pale yellow oil.

3-Methylene-6-phenyl-1-tosyl-1,2,3,4-tetrahydropyridine (5a)

Yield 94%; yellow needles (AcOEt/hexane, mp 83.7–85.0 ºC); IR (neat) 1350, 1163, 763, 695 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl$_3$) δ 2.40 (3H, s), 2.57–2.85 (2H, m), 4.23 (2H, s), 4.66 (1H, s), 4.81 (1H, s), 5.68 (1H, t, *J* = 4.0 Hz), 7.19 (2H, d, *J* = 8.4 Hz), 7.31–7.37 (3H, m), 7.51–7.53 (4H, m); ^{13}C-NMR (100 MHz, CDCl$_3$) δ 21.5 (CH$_3$), 29.9 (CH$_2$), 53.2 (CH$_2$), 112.1 (CH$_2$), 120.1 (CH), 126.6 (CH), 128.0 (CH), 128.1 (CH), 128.3 (CH), 128.9 (CH), 135.4 (Cq), 138.1 (Cq), 138.7 (Cq), 140.3 (Cq), 143.4 (Cq); HRMS (ESI) *m/z* calcd for $C_{19}H_{19}NNaO_2S$ [M+Na]$^+$ 348.1034, found 348.1033.

3-Methylene-6-(4-methylphenyl)-1-tosyl-1,2,3,4-tetrahydropyridine (5b)

Yield 93%; yellow needles (AcOEt/hexane, mp 108.5–111.8 ºC); IR (neat) 1352, 1164, 813, 691 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl$_3$) δ 2.36 (3H, s), 2.39 (3H, s), 2.54 (2H, s), 4.22 (2H, s), 4.65 (1H, s), 4.80 (1H, s), 5.63 (1H, t, *J* = 4.0 Hz), 7.15 (2H, d, *J* = 8.0 Hz), 7.17 (2H, d, *J* = 8.0 Hz), 7.41 (2H, d, *J* = 8.0 Hz), 7.52 (2H, d, *J* = 8.0 Hz); ^{13}C-NMR (100 MHz, CDCl$_3$) δ 21.2 (CH$_3$), 21.5 (CH$_3$), 29.9 (CH$_2$), 53.2 (CH$_2$), 111.9 (CH$_2$), 119.2 (CH), 126.5 (CH), 128.3 (CH), 128.7 (CH), 128.8 (CH), 135.4 (Cq), 135.9 (Cq), 137.9 (Cq), 138.3 (Cq), 140.3 (Cq), 143.3 (Cq); HRMS (ESI) *m/z* calcd for $C_{20}H_{21}NNaO_2S$ [M+Na]$^+$ 362.1191, found 362.1190.

6-(4-Methoxyphenyl)-3-methylene-1-tosyl-1,2,3,4-tetrahydropyridine (5c)

Yield 91%; orange needles (AcOEt/hexane, mp 51.3–54.9 ºC); IR (neat) 1606, 1509, 1349, 1249, 1163 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl$_3$) δ 2.40 (3H, s), 2.54–2.55 (2H, m), 3.83 (3H, s), 4.22 (2H, s), 4.66 (1H, s), 4.82 (1H, s), 5.57 (1H, t, *J* = 4.2 Hz), 6.88 (2H, d, *J* = 8.8 Hz), 7.18 (2H, d, *J* = 8.0 Hz), 7.44 (2H, d, *J* = 8.8 Hz), 7.51 (2H, d, *J* = 8.0 Hz); ^{13}C-NMR (100 MHz, CDCl$_3$) δ 21.5 (CH$_3$), 29.8 (CH$_2$), 53.3 (CH$_2$), 55.3 (CH$_3$), 111.9 (CH$_2$), 113.4 (CH), 118.4 (CH), 127.9 (CH), 128.3 (CH), 128.8 (CH), 131.3 (Cq), 135.4 (Cq), 138.4 (Cq), 139.9 (Cq), 143.3 (Cq), 159.6 (Cq); HRMS (ESI) *m/z* calcd for $C_{20}H_{21}NNaO_3S$ [M+Na]$^+$ 378.1140, found 378.1135.

6-(3-Methoxyphenyl)-3-methylene-1-tosyl-1,2,3,4-tetrahydropyridine (5d)

Yield 91%; colorless needles (AcOEt/hexane, mp 105.0–107.0 ºC); IR (neat) 1352, 1163, 1040, 776 cm^{-1}; ^{1}H-NMR (400 MHz, CDCl$_3$) δ 2.39 (3H, s), 2.56–2.57 (2H, m), 3.82 (3H, s), 4.22 (2H, s), 4.67 (1H, s), 4.82 (1H, s), 5.69 (1H, t, *J* = 4.0 Hz), 6.84–6.86 (1H, m), 7.03–7.04 (1H, m), 7.10–7.12 (1H, m), 7.18 (2H, d, *J* = 8.0 Hz), 7.23–7.27 (1H, m), 7.53 (2H, d, *J* = 8.0 Hz); ^{13}C-NMR (100 MHz, CDCl$_3$) δ 21.5 (CH$_3$), 29.9 (CH$_2$), 53.2 (CH$_2$), 55.2 (CH$_3$), 112.0 (CH$_2$), 112.4 (CH), 113.6 (CH), 119.2 (CH), 120.3 (CH), 128.3 (CH), 128.9 (CH), 128.9 (CH), 135.5 (Cq), 136.3 (Cq), 138.2 (Cq), 140.0 (Cq), 143.4 (Cq), 159.3 (Cq); HRMS (ESI) *m/z* calcd for $C_{20}H_{21}NNaO_3S$ [M+Na]$^+$ 378.1140, found 378.1136.

6-(4-Fluorophenyl)-3-methylene-1-tosyl-1,2,3,4-tetrahydropyridine (5e)

Yield 87%; yellow needles (AcOEt/hexane, mp 109.5–111.5 °C); IR (neat) 1507, 1351, 1221, 1164 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.40 (3H, s), 2.57–2.58 (2H, m), 4.22 (2H, s), 4.67 (1H, s), 4.82 (1H, s), 5.62 (1H, t, *J* = 4.2 Hz), 7.03 (2H, t, *J* = 8.8 Hz), 7.19 (2H, d, *J* = 8.4 Hz), 7.46–7.52 (4H, m); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 29.9 (CH_2), 53.2 (CH_2), 112.2 (CH_2), 114.9 (CH, d, *J* = 21.5 Hz), 119.8 (CH), 128.3 (CH, d, *J* = 7.5 Hz), 128.3 (CH), 128.9 (CH), 134.9 (Cq), 135.3 (Cq), 137.9 (Cq), 139.4 (Cq), 143.5 (Cq), 162.7 (Cq, d, *J* = 246.2 Hz); HRMS (ESI) *m/z* calcd for $C_{19}H_{18}FNNaO_2S$ [M+Na]$^+$ 366.0940, found 366.0941.

3-Methylene-6-(naphthalen-2-yl)-1-tosyl-1,2,3,4-tetrahydropyridine (5f)

Yield 92%; colorless needles (AcOEt/hexane, mp 139.3–142.1 °C); IR (neat) 1351, 1164, 771, 669 cm^{-1}; ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.39 (3H, s), 2.64–2.65 (2H, m), 4.30 (2H, s), 4.71 (1H, s), 4.86 (1H, s), 5.81 (1H, t, *J* = 4.0 Hz), 7.18 (2H, d, *J* = 8.4 Hz), 7.45–7.49 (2H, m), 7.54 (2H, d, *J* = 8.4 Hz), 7.66–7.68 (1H, m), 7.80–7.84 (3H, m), 7.92 (1H, s); ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.5 (CH_3), 30.1 (CH_2), 53.2 (CH_2), 112.1 (CH_2), 120.7 (CH), 125.1 (CH), 125.3 (CH), 125.9 (CH), 126.0 (CH), 127.4 (CH), 127.7 (CH), 128.2 (CH), 128.3 (CH), 128.9 (CH), 133.2 (Cq), 133.3 (Cq), 135.6 (Cq), 136.2 (Cq), 138.2 (Cq), 140.4 (Cq), 143.4 (Cq); HRMS (ESI) *m/z* calcd for $C_{23}H_{21}NNaO_2S$ [M+Na]$^+$ 398.1191, found 398.1196.

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