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Generation and cycloaddition of polymer-supported azomethine ylide by utilizing the characteristics of silicon: a facile route to pyrrolidines and pyrroles from α-silylimines bound to resin

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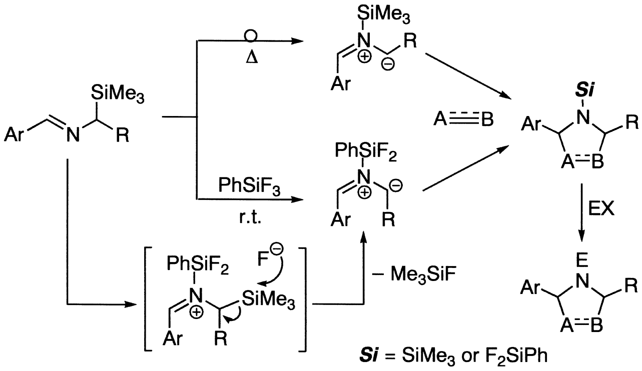
Abstract—The solid-phase synthesis of pyrrolidine and pyrrole derivatives using polymer-supported α-silylimines is described. Polymer-supported azomethine ylides were generated from the corresponding α-silylimine by thermal 1,2-silatropy onto the imino nitrogen or by treatment with a trifluorosilane as a quaternization and desilylation reagent, and the resulting species were then reacted with dipolarophiles to give five-membered heterocycles. © 2002 Elsevier Science Ltd. All rights reserved.

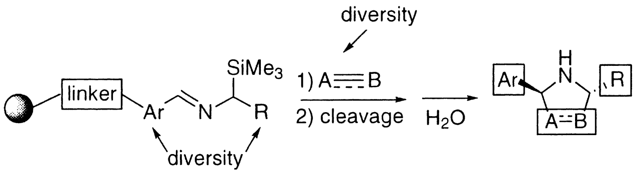
1. Introduction

Solid-phase organic synthesis (SPOS)[1] is currently an important technique, because of its potential for use in combinatorial chemistry and high-throughput screening.[2] Heterocycles have been the subject of special attention in combinatorial synthesis due to their interesting properties that make them useful in pharmaceuticals, agrochemicals, and a number of other functional organic materials.[3] One of the most useful methods for the synthesis of diverse heterocyclic compounds involves 1,3-dipolar cycloaddition reactions,[4] and, in the past few years, a considerable number of solid-phase syntheses of heterocycles using 1,3-dipolar cycloaddition have been reported[5] including our recent procedure.[6] In a series of studies[7] on the generation of 1,3-dipoles in solution phase, we discovered that azomethine ylides can be generated from α-silylimines by thermal 1,2-silatropy onto the imino nitrogen or by treatment with a trifluorosilane as a quaternization and desilylation reagent (Scheme 1). The former method has advantages, in that no additives are required and the reactions can be performed under completely neutral conditions. In the latter method, a fluorosilane plays multiple functions and the reaction proceeds under mild conditions. These methods are based on the strong affinity between silicon and nitrogen or fluorine. The resulting *N*-silylated azomethine ylides are quite useful species in terms of the simultaneous formation of two C–C bonds leading to *N*-unsubstituted and *N*-substituted heterocycles.

Simple procedures using mild conditions as well as those having diversity in substituents of building blocks are highly desirable in the solid-phase synthesis of a variety of heterocycles. If a polymer is attached to an α-silylimine, a potential precursor of an azomethine ylide, this would greatly enhance the versatility for the construction of libraries of heterocycles as shown in Scheme 2. From these points of view, we report here on the solid-phase synthesis of five-membered *N*-heterocycles from polymer-supported α-silylimines by utilizing the characteristics of silicon.



Scheme 1.



Scheme 2.

Keywords: azomethine ylide; 1,3-dipolar cycloaddition; solid-phase synthesis; 1,2-silatropy; pyrrolidine; pyrrole.

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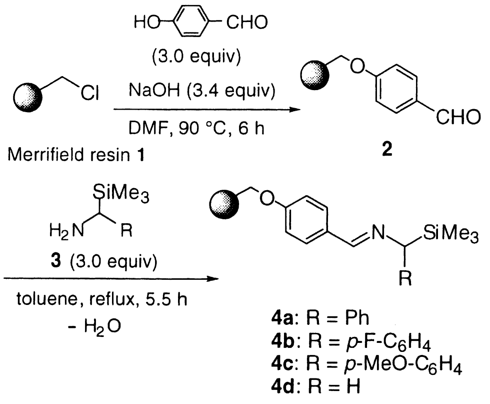
2. Results and discussion

α-Silylimines bound to resin were designed and prepared according to Scheme 3. Treatment of commercially available Merrifield resin **1** with *p*-hydroxybenzaldehyde under basic conditions gave resin, **2**, which contains a formyl group. The desired imines were readily synthesized by condensing resin **2** with α-(trimethylsilyl)amines in toluene under Dean–Stark conditions. The progress of the reaction was monitored directly by FT-IR and ^{1}H MAS NMR without cleavage of each product from the resins. Representative spectra in the course of the preparation of resin **4** (R=Ph) from resin **1** are shown in Figure 1(a) and (b). As evidenced by FT-IR measurement carbonyl group (1694 cm^{-1}) on resin **2** completely disappeared on conversion to resin **4a**. In NMR studies, signals derived from the target resin could be successfully assigned, and no signals corresponding to the starting resins were observed in each of the steps, indicating that the reactions on the solid phase proceeded in nearly quantitative yields.



Scheme 3.

The prepared polymer-supported α-silylimine **4a** was first employed in our original method for generating an azomethine ylide by thermal 1,2-silatropy (Method A in Table 1). Resin **4a** was reacted with *N*-phenylmaleimide (NPMI) in toluene at 180°C for 6 h. Cleavage of the end products from the resin was accomplished with TFA in CH_2Cl_2 to afford the corresponding cycloadducts in 83% yield (overall yield through four steps). Although the solid-phase synthesis is exceptionally efficient, the stereoselectivity was found to be rather low under the present conditions. Thus, an alternative method using a trifluorosilane (Method B) was adopted to α-silylimine **4a** bound to resin. Resin **4a** was treated with NPMI in the presence of trifluorophenylsilane (1.2 equiv.) in toluene at 40°C for 48 h, followed by cleavage with TFA, giving the pyrrolidine derivatives in 81% yield with high stereoselectivity.

To evaluate the stereochemistry of the solid-phase synthesis using a trifluorosilane, the corresponding reaction in solution phase was carried out (Table 2). An α-silylimine having a benzyloxy substituent at the *para* position of the phenyl ring conjugated with the imino group was tested as a model compound in the solution phase experiment. A lower stereoselectivity in the solution phase was observed, compared to the solid phase, and the product yield in the case of the solid-phase synthesis was higher (through four steps; 81% yield vs. via one step; 76% yield). Although the reasons for the difference in the stereochemistry are unclear at present, the results provide a demonstration of the versatility of the solid-phase synthesis from the point of view of stereochemistry.

Since the method for generating an azomethine ylide using a trifluorosilane (Method B) was found to be critical in the solid-phase heterocyclic synthesis, some polymer-supported α-silylimines **4** were examined in the cycloaddition (Table 3). The reaction of *p*-fluorophenyl-substituted α-silylimine bound to resin **4b** with NPMI was performed in toluene at 40°C for 6 h, providing the corresponding cycloadduct in

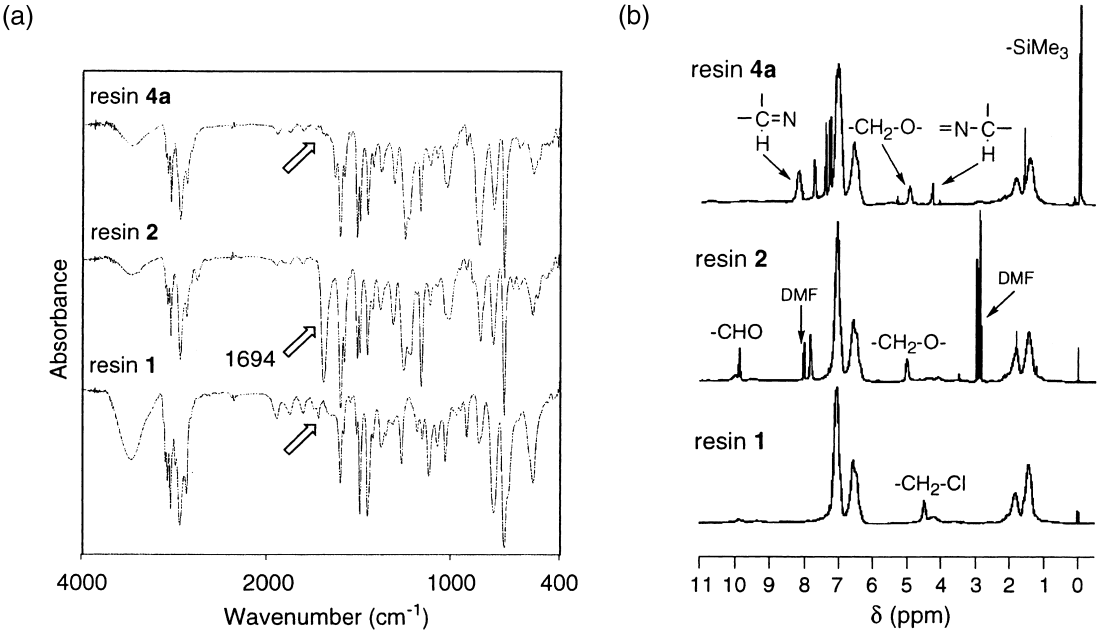
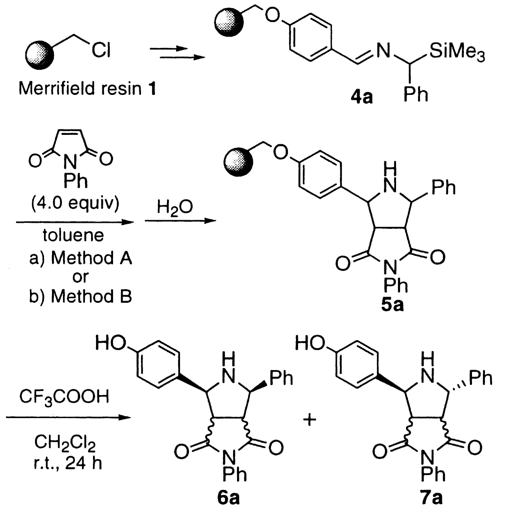


Figure 1. (a) FT-IR spectra of the resins; (b) ^{1}H MAS NMR spectra of resins.

Table 1. Cycloaddition of resin **4a** with MPMI by two methods

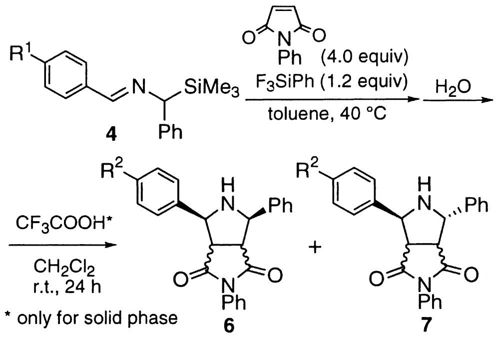


	F_3SiPh (equiv.)	Temperature (°C)	Time (h)	Yield[a] (%) (**6a**[b]/**7a**[c])
Method A	–	180	6	83 (36:64)
Method B	1.2	40	48	81 (93:7)

[a] Overall yield through four steps.
[b] *endo*/*exo*=ca. 40:60.
[c] *endo*/*exo*=ca. 50:50.

good overall yield. The silylimine bearing an electron-donating group (MeO) instead of a fluoro group was also employed in the reaction to afford the desired pyrrolidine in 70% yield. It is noteworthy that the procedure can be applied to the generation of a less-stabilized azomethine ylide which does not bear ylide-stabilizing substituents on each carbon. Namely, resin **4d**, containing no substituents α to the imino nitrogen, was treated with the fluorosilane to generate the less-stabilized ylide and the subsequent cycloaddition proceeded smoothly. Elevation of the temperature to 60°C resulted in an improvement in yield.

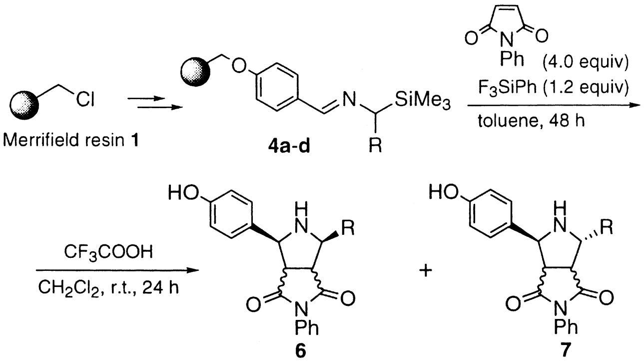
Table 2. Stereoselectivity: solid-phase vs. solution-phase synthesis



R^1	R^2	Time (h)	Yield (%) (**6**:**7**[a])
 O	HO	48	81 (93[b]:7)
BnO	BnO	24	76 (80[c]:20)

[a] *endo*/*exo*=ca. 50:50.
[b] *endo*/*exo*=ca. 40:60.
[c] *endo*/*exo*=ca. 60:40.

Table 3. Cycloaddition of resin **4a–d** with NPMI

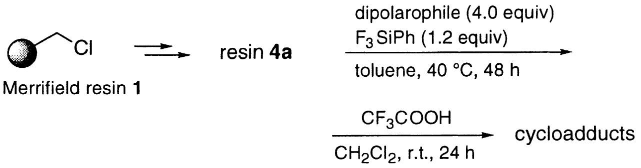


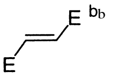
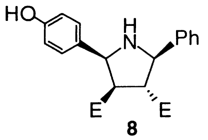
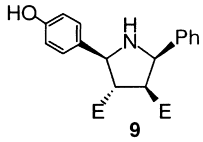
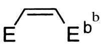
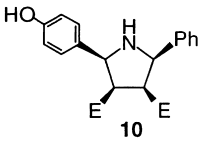
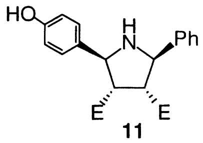
R		Temperature (°C)	Yield[a] (%) (**6**/**7**[b])
Ph	**4a**	40	81 (93[c]: 7)
p-FC$_6$H$_4$	**4b**	40	61 (77[d]:23)
p-MeOC$_6$H$_4$	**4c**	40	70 (74[b]:26)
H	**4d**	40	44
H	**4d**	60	71

[a] Overall yields through four steps.
[b] *endo*/*exo*=ca. 50:50.
[c] *endo*/*exo*=ca. 40:60.
[d] *endo*/*exo*=ca. 60:40.

To prepare more diverse pyrrolidines, acyclic olefinic (Table 4) and acetylenic (Scheme 4) dipolarlophiles were employed in the solid-phase synthesis. Treatment of resin **4a** with dimethyl fumarate in the presence of the trifluorosilane under standard conditions, followed by a cleavage operation with TFA, gave tetrasubstituted pyrrolidines **8** and **9** in 53% yield. Dimethyl maleate, a geometric isomer also underwent cycloaddition to yield pyrrolidines. While the stereoselectivities of these reactions were not satisfactory, retention of the stereochemistry of the two carbon centers derived from the dipolarophiles was obtained in both cases, suggesting that a concerted cycloaddition took place in the solid phase.

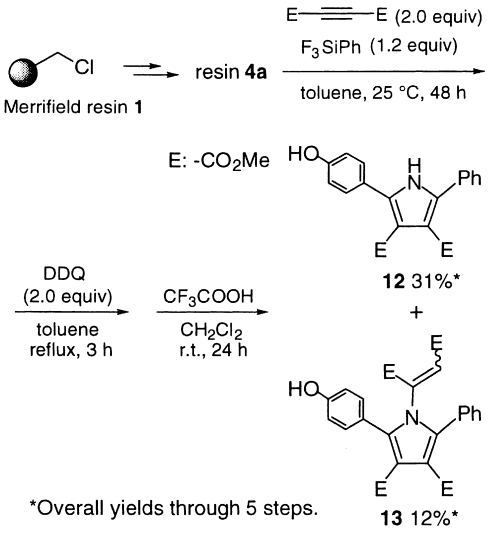
Table 4. Cycloaddition of resin **4a** with acyclic olefinic dipolarlophiles



Dipolarophiles	Cycloadducts/yield[a] (ratio)	
	 **8**	 **9**
	53% (55 :	45)
	 **10**	 **11**
	43% (70 :	30)

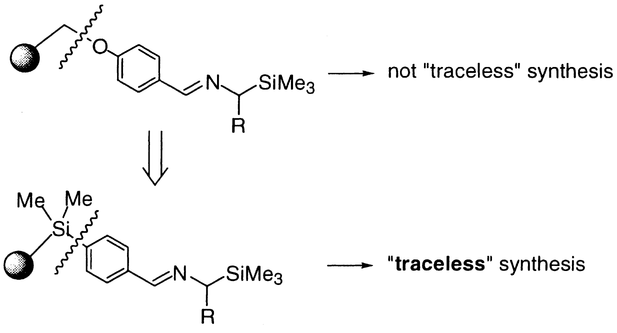
[a] Overall yields through four steps.
[b] E: $-CO_2Me$.

Dimethyl acetylenedicarboxylate (DMAD) as an acetylenic dipolarophile was adopted to the solid-phase synthesis. In order to obtain an aromatic heterocycle, an oxidation step was introduced after the cycloaddition by which a pyrrole derivative bound to resin would be formed. The prepared resin **4a** was reacted with DMAD (2 equiv.) in the presence of trifluorophenylsilane (1.2 equiv.), followed by treatment with DDQ and TFA under the conditions shown in Scheme 4, to give, expectedly, an *N*-unsubstituted pyrrole derivative along with a Michael adduct. The formation of the by-product can be explained by the partial insertion of excessive DMAD to the Si–N bond of the initial cycloadduct, 3-pyrroline bound to resin.



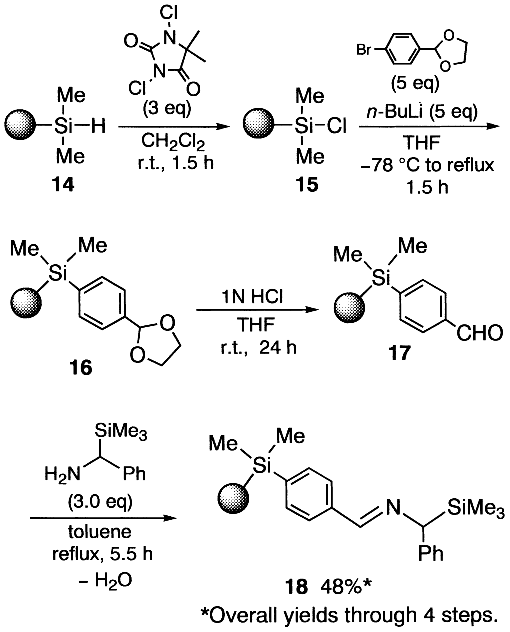
Scheme 4.

Although the method described thus far is suitable for the synthesis of a variety of five-membered *N*-heterocycles with diversity in several substituents, it is not a traceless solid-phase synthesis. To overcome this limitation, an alternative polymer-supported α-silylimine having a silyl group in a linker unit was designed, as shown in Scheme 5. If the silyl group is introduced to the linker moiety, a traceless synthesis would be expected.

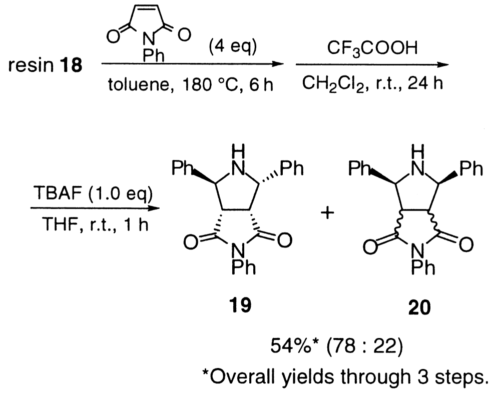


Scheme 5.

Chlorination of the starting resin **14**, subsequent phenylation, deprotection, and condensation proceeded smoothly to give the desired resin **18** (Scheme 6). The cycloaddition of resin **18** with NPMI was performed at elevated temperature, followed by a cleavage operation to afford the corresponding pyrrolidines **19** and **20** which contain no OH group derived from the resin (Scheme 7). Thus, the modification of the linker moiety permitted a 'traceless' solid-phase pyrrolidine synthesis.



Scheme 6.



Scheme 7.

3. Conclusion

In summary, we report on the development of a novel solid-phase synthesis of pyrrolidine and pyrrole derivatives from polymer-supported α-silylimines by utilizing the characteristics of silicon. Polymer-supported azomethine ylides were generated from the corresponding α-silylimines by thermal 1,2-silatropy or by treatment with a trifluorosilane, and the resulting species were then reacted with dipolarophiles. A modification of the linker led to a traceless solid-phase synthesis. We also demonstrated reagent versatility in several steps, suggesting that these methods are potent candidates for the construction of a library of the heterocycles.

4. Experimental

4.1. General methods

Melting points were determined on a Yanagimoto micro melting point apparatus and are uncorrected. IR spectra were obtained on a Jasco FT/IR-410 Fourier transform infrared spectrophotometer. ^{1}H and ^{13}C NMR spectra were recorded on a JEOL FT-NMR JNM EX 270 spectrometer (^{1}H NMR, 270 MHz; ^{13}C NMR, 68 MHz) using tetramethylsilane as an internal standard. Mass spectra were measured using a Shimadzu Model GCMS-QP5000 spectrometer. High resolution mass spectral data were obtained on a JEOL DX-303 mass spectrometer. Elemental analyses were performed at the Analytical Center, Faculty of Engineering, Osaka University. Flash column chromatography (FCC) was performed using silica gel BW-300 (Fuji Silysia Chemical Co.). Preparative gel permeation liquid chromatography (GPLC) was performed on a JAI (Japan Analytical Industry) LC-908 instrument with JAIGEL 1H-2H columns and chloroform as an eluent. Analytical thin layer chromatography was performed using EM reagent 0.25 mm silica gel 60-F plates. Visualization was accomplished with UV light and ethanolic phosphomolybdic acid followed by heating. All reactions were carried out under an atmosphere of nitrogen. Organic solvents were dried and distilled prior to use. The yield of compounds are calculated on the basis of the initial loading of the starting resin except for resin **18**.

4.2. Representative procedure for preparation of resin 4a

To a suspension of *p*-hydroxybenzaldehyde (1.61 g, 13.2 mmol) in DMF (40 mL) was added NaOH (598 mg, 15.0 mmol) and the resulting mixture was stirred at room temperature for 2 h. Merrified resin **1** (purchased from Novabiochem, loading level=1.1 mmol/g, 4.00 g, 4.40 mmol) was added to the mixture and stirred at 90°C for 6 h. The resin was filtered and washed sequentially with DMF (20 mL), DMF/H_2O (a 1/1 mixture, 10 mL), H_2O (20 mL), DMF/H_2O (a 1/1 mixture, 20 mL), DMF (20 mL), CH_2Cl_2 (2×40 mL), and Et_2O (40 mL), and dried in vacuo to give resin **2** (4.56 g).

After suspension of resin **2** (4.27 g, 4.13 mmol) in toluene (43 mL) was sonicated for 10 min, α-(trimethylsily)benzylamine **3** (2.22 g, 12.4 mmol) was added, and condensed for 5.5 h under Dean–Stark condition. The resin was filtered and washed sequentially with toluene (40 mL), CH_2Cl_2 (2×40 mL), and Et_2O (40 mL), and dried in vacuo to give resin **4a** (5.21 g); IR (KBr) 3025, 2922, 1632, 1604, 1508, 1453, 1377, 1307, 1255, 1164, 1108 cm^{-1}.

4.3. Representative procedure for generation and cycloaddition of azomethine ylides from resin 2 by thermal 1,2-silatropy (Method A)

To a suspension of resin **4a** (500 mg, 0.36 mmol) in toluene (5 mL) was added *N*-phenylmaleimide (249 mg, 1.44 mmol) and the resulting mixture was heated at 180°C in a sealed tube for 6 h. After cooling to room temperature, the resin was filtered and washed sequentially with MeOH (2×5 mL), CH_2Cl_2 (2×5 mL), and Et_2O (2×5 mL), and dried in vacuo to give resin **5a**; IR (KBr) 3026, 2922, 1718, 1601, 1493, 1452, 1379, 1169, 1111, 1030 cm^{-1}.

4.4. Representative procedure for generation and cycloaddition of azomethine ylides from resin 2 by treatment with trifluorosilane (Method B)

To a suspension of resin **4a** (400 mg, 0.32 mmol) in toluene (4 mL) was added *N*-phenylmaleimide (219 mg, 1.27 mmol) and trifluorosilane (61.6 mg, 0.38 mmol), then the resulting mixture was stirred for 48 h at 40°C. The resin was filtered and washed sequentially with MeOH (2×5 mL), CH_2Cl_2 (2×5 mL), and Et_2O (2×5 mL), and dried in vacuo to give resin **5a**.

4.5. Representative procedure for cleavage of polymer-supported cycloadduct 5a

After a suspension of resin **5a** (0.32 mmol) in TFA/CH_2Cl_2 (a 1/1 mixture, 4 mL) was agitated for 24 h, the resin was filtered and washed sequentially with MeOH (3×5 mL), CH_2Cl_2 (1×5 mL), and Et_2O (3×5 mL), then the filtrate was concentrated. The residue was neutralized with $NaHCO_3$ aq., extracted with CH_2Cl_2 (2×20 mL), and dried over $MgSO_4$, and the solvent was removed under reduced pressure. The residue was purified by chromatography on SiO_2 to give 3-(4-hydroxyphenyl)-2,6-dioxo-1,5-triphenyl-1,4-diazabicyclo[3.3.0]octane (**6a**) (*endo*: 55.8 mg, 46% *exo*: 35.0 mg, 29%), and **7a** (7.6 mg, 6%).

4.5.1. 3-(4-Hydroxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-diazabicyclo[3.3.0]octane (6a *exo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (12%), and H-5 and H-8 (12%). colorless needles; mp 173°C; IR (KBr) 1709, 1385, 1171 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.30 (br s, 1H, NH), 3.49–3.59 (m, 2H, –CH), 4.63 (d, J=7.8 Hz, 1H, –NCH), 4.66 (d, J=7.6 Hz, 1H, –NCH), 5.80 (br s, 1H, OH), 6.70 (d, J=8.4 Hz, 2H, ArH), 7.12–7.54 (m, 12H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 49.7 (CH), 49.8 (CH), 63.8 (NCH), 63.9 (NCH), 115.2, 125.9, 127.0, 127.7, 127.8, 128.0, 128.1, 128.3, 128.6, 131.8, 137.8, 156.6 (ArC), 174.0 (CO), 174.1 (CO); MS *m/z* 383 (M$^+$), 290, 116; HRMS calcd for $C_{24}H_{20}N_2O_3$: 384.1474. Found: 384.1476.

4.5.2. 3-(4-Hydroxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-diazabicyclo[3.3.0]octane (6a *endo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (0%), and H-5 and H-8 (0%). white solid; mp 220°C; IR (KBr) 1715, 1371, 1169 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.40 (br s, 1H, NH), 3.38–3.50 (m, 2H, CH), 4.45 (d, J=6.5 Hz, 1H, NCH), 4.52 (d, J=6.8 Hz, 1H, NCH), 6.84 (d, J=8.4 Hz, 2H, ArH), 7.23–7.70 (m, 12H, ArH); ^{13}C NMR ($CDCl_3$+d_6-DMSO, 68 MHz) δ 53.5 (2×CH), 64.4 (NCH), 64.5 (NCH), 115.2, 126.1, 126.6, 127.4, 127.7, 128.1, 128.2, 128.6, 131.1, 131.4, 140.8, 156.6 (ArC), 175.4 (CO), 175.5 (CO); MS *m/z* 383 (M$^+$), 290, 116; HRMS calcd for $C_{24}H_{20}N_2O_3$: 384.1474. Found: 384.1469.

4.5.3. 3-(4-Fluorophenyl)-5-(4-hydroxyphenyl)-2,6-(dioxo-1-phenyl-1,4-diazabicyclo[3.3.0] octane (6b *exo*).

Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (16%), and H-5 and H-8 (15%). colorless plates; mp 252°C; IR (KBr) 1701, 1389, 1219, 1176 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.32 (br s, 1H, NH), 3.38–3.56 (m, 2H, CH), 4.67 (br s, 2H, NCH), 6.77 (d, J=8.9 Hz, 2H, ArH), 7.04–7.54 (m, 11H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 49.8 (2×CH), 63.3 (NCH), 63.8 (NCH), 115.3 (d, J_{C-F}=44 Hz, ArC), 115.3, 126.0, 127.1, 128.2, 128.4, 128.6, 128.7, 128.9, 129.0, 131.5, 133.3, 155.8 (ArC), 162.2 (d, J_{C-F}=246 Hz, ArC), 174.3 (CO), 175.4 (CO); MS *m/z* 308, 134; HRMS calcd for $C_{24}H_{19}FN_2O_3$: 402.1380. Found: 402.1369.

4.5.4. 3-(4-Fluorophenyl)-5-(4-hydroxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo[3.3.0]octane (6b *endo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (0%), and H-5 and H-8 (3%). yellow solid; mp 218°C; IR (KBr) 1703, 1385, 1219, 1186 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.39–3.42 (m, 2H, CH), 4.44–4.50 (m, 2H, NCH), 6.86–7.69 (m, 13H, ArH); ^{13}C NMR ($CDCl_3$+d_6-DMSO, 68 MHz) δ 53.3 (CH), 53.5 (CH), 63.7 (NCH), 64.4 (NCH), 115.0 (d, J_{C-F}=21 Hz, ArC), 115.3, 126.1, 127.7, 128.2, 128.3, 128.7, 131.1, 131.3, 136.7, 136.7, 156.7 (ArC), 161.9 (d, J_{C-F}=246 Hz, ArC), 175.3 (CO), 175.5 (CO); MS *m/z* 308, 134; HRMS calcd for $C_{24}H_{19}FN_2O_3$: 402.1380. Found: 402.1382.

4.5.5. 5-(4-Hydroxyphenyl)-3-(4-methoxyphenyl)-2,6-dioxo-1,4-diazabicyclo[3.3.0] octane (6c, *exo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (15%), and H-5 and H-8 (15%). yellow needles; mp 242°C; IR (KBr) 1711, 1385, 1248, 1169 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.36 (m, 2H, CH), 3.68 (s, 3H, OMe), 4.46 (br s, 2H, NCH), 6.56 (d, J=8.1 Hz, 2H, ArH), 6.81 (d, J=8.1 Hz, 2H, ArH), 7.05 (d, J=7.6 Hz, 2H, ArH), 7.20–7.35 (m, 7H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 49.9 (2×CH), 55.2 (OMe), 63.6 (NCH), 63.8 (NCH), 113.6, 115.3, 126.1, 128.2, 128.3, 128.9, 129.6, 131.6, 155.7, 159.1 (ArC), 174.5 (CO), 177.5 (CO); Anal. calcd for $C_{25}H_{22}N_2O_4$: C, 72.45; H, 5.35; N, 6.76. Found: C, 72.16; H, 5.34; N, 6.57; HRMS calcd for $C_{25}H_{22}N_2O_4$: 414.1579. Found: 414.1574.

4.5.6. 5-(4-Hydroxyphenyl)-3-(4-methoxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo-[3.3.0] octane (6c *endo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (5%), and H-5 and H-8 (5%). white needles; mp 171°C; IR (KBr) 1711, 1385, 1250, 1180 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.34–3.36 (m, 2H, CH), 3.76 (s, 3H, OMe), 4.37 (m, 2H, NCH), 6.77 (d, J=8.0 Hz, 2H, ArH), 6.87 (d, J=8.6 Hz, 2H, ArH), 7.19–7.53 (m, 9H, ArH); ^{13}C NMR ($CDCl_3$+d_6-DMSO, 68 MHz) δ 53.7 (CH), 53.7 (CH), 55.2 (OMe), 64.3 (NCH), 64.6 (NCH), 113.8, 115.4, 126.2, 127.8, 128.3, 128.8, 131.5, 131.5, 132.9, 156.7, 159.0 (ArC), 175.6 (CO), 175.7 (CO); HRMS calcd for $C_{25}H_{22}N_2O_4$: 414.1579. Found: 414.1571.

4.5.7. 3-(4-Hydroxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo[3.3.0]octane (6d *exo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (14%). yellow solid; mp 126°C; IR (KBr) 1705, 1385, 1178 cm^{-1} ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.22 (dd, J=9.5, 7.0 Hz, 1H, C*H*H), 3.48–3.57 (m, 2H, CH), 3.77 (d, J=9.5 Hz, 1H, CH*H*), 4.40 (d, J=7.8 Hz, Hz, 1H, NCH), 6.70 (d, J=6.5 Hz, 2H, ArH), 7.16–7.42 (m, 8H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 46.2 (CH), 49.2 (CH), 49.3 (NCH_2), 65.5 (NCH), 115.2, 126.0, 128.1, 128.3, 128.9, 130.0, 131.7, 155.5 (ArC), 175.3 (CO), 178.2 (CO); HRMS calcd for $C_{18}H_{16}N_2O_3$: 308.1161. Found: 308.1169.

4.5.8. 3-(4-Hydroxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo[3.3.0]octane (6d *endo*). Red solid; mp 56–58°C; IR (KBr) 1711, 1389, 1176 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.39–3.48 (m, 4H, 2×CH, C*HH*), 4.63 (s, 1H, NCH), 6.73 (d, J=8.6 Hz, 2H, ArH), 7.16–7.42 (m, 8H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 46.5 (CH), 49.1 (CH), 52.9 (CH_2), 64.9 (NCH), 64.9 (NCH), 115.4, 126.2, 127.4, 128.5, 129.0, 131.6, 133.2, 154.7, (ArC), 177.0 (C)O), 177.6 (CO); HRMS calcd for $C_{18}H_{16}N_2O_3$: 308.1161. Found: 308.1157.

4.5.9. 3-(4-Benzyloxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-diazabicyclo[3.3.0]octane (6 *exo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (15%), and H-5 and H-8 (14%). colorless liquid; IR (neat) 1714, 1170 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.30 (br. s, 1H, NH), 3.49–3.58 (m, 2H, CH), 4.64–4.67 (m, 2H, NCH), 5.06 (s, 2H, OCH_2), 6.97–7.56 (m, 19H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 49.8 (CH), 49.8 (CH), 63.7 (NCH), 64.1 (NCH), 69.9 (OCH_2), 114.4, 125.9, 127.1, 127.4, 127.8, 127.9, 128.0, 128.2, 128.2, 128.4, 128.8, 129.4, 131.8, 136.8, 137.8, 158.4, (ArC), 174.1 (CO), 174.1 (CO) 174.2 (CO); HRMS calcd for $C_{31}H_{26}N_2O_3$: 474.1943. Found: 474.1946.

4.5.10. 3-(4-Benzyloxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-diazabicyclo[3.3.0]octane (6 *endo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (4%) and H-5 and H-8 (4%). colorless liquid; IR (neat) 1713, 1173 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.41 (br. s, 1H, NH), 3.37–3.48 (m, 2H, CH), 4.46 (d, J=6.8 Hz, 1H, NCH), 4.54 (d, J=6.2 Hz, 1H, NCH), 5.08 (s, 2H, OCH_2), 7.00–7.69 (m, 19H, ArH); ^{13}C NMR ($CDCl_3$ 68 MHz) δ 53.7 (CH), 54.0 (CH), 64.6 (NCH), 64.7 (NCH), 70.1 (OCH_2), 114.9, 126.3, 126.8, 127.4, 127.9, 127.9, 128.0, 128.5, 128.6, 129.0, 131.6, 133.1, 136.8, 141.0, 158.5 (ArC), 175.6 (CO), 175.7 (CO) 175.7 (CO); HRMS calcd for $C_{31}H_{26}N_2O_3$: 474.1943. Found: 474.1946.

4.5.11. 3-(4-Hydroxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-diazabicyclo[3.3.0]octane (7a). Yellow solid; mp 235°C; IR (KBr) 1709, 1387 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 1.65 (br. s, 1H, NH), 3.62–3.70 (m, 2H, CH), 4.82 (d, J=8.4 Hz, 1H, NCH), 5.13 (s, 1H, NCH), 6.85 (d, J=8.6 Hz, 2H, ArH), 7.14–7.44 (m, 12H, ArH); ^{13}C NMR ($CDCl_3$+d_6-DMSO, 68 MHz) δ 49.5 (CH), 51.8 (CH), 61.8 (NCH), 62.3 (NCH), 115.1, 125.7, 126.5, 126.7, 127.3, 127.6, 127.6, 128.3, 131.5, 131.6, 137.8, 156.1 (ArC), 174.0 (CO), 177.0 (CO); MS *m/z* 383 (M$^+$), 290, 116; HRMS calcd for $C_{24}H_{20}N_2O_3$: 384.1474. Found: 384.1469.

4.5.12. 3-(4-Hydroxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-daizabicyclo[3.3.0]octane (another isomer of 7a). White solid; mp 173°C; IR (KBr) 1701, 1383 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.35 (br s, 1H, NH), 3.61 (dd, J=8.4, 7.8 Hz, 1H, CH), 3.73 (d, J=7.8 Hz, 1H, CH), 4.80 (d, J=8.4 Hz, 1H, NCH), 5.18 (s, 1H, NCH), 6.70 (d, J=8.7 Hz, 2H, ArH), 7.19–7.47 (m, 12H, ArH); ^{13}C NMR (CDCl$_3$ 68 MHz) δ 49.8 (CH), 52.2 (CH), 62.0 (NCH), 62.9 (NCH), 115.2, 125.7, 126.0, 127.5, 128.2, 128.3, 128.8, 128.9, 129.6, 131.6, 141.3, 155.4 (ArC), 174.9 (CO), 177.3 (CO); MS m/z 383 (M^{+}), 290, 116; HRMS calcd for $\mathrm{C_{24}H_{20}N_2O_3}$: 384.1474. Found: 384.1475.

4.5.13. 3-(4-Fluorophenyl)-5-(4-hydroxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo[3.3.0] octane (7b). Yellow solid; mp 100–103°C; IR (KBr) 1705, 1390, 1219, 1160 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.63 (dd, J=8.1, 7.8 Hz, 1H, CH), 3.69 (d, J=7.8 Hz, 1H, CH), 4.80 (d, J=8.1 Hz, 1H, NCH), 5.12 (s, 1H, NCH), 6.87 (d, J=8.1 Hz, 2H, ArH), 6.99–7.46 (m, 11H, ArH); ^{13}C NMR (CDCl$_3$+d_6-DMSO, 68 MHz) δ 49.7 (CH), 51.9 (CH), 61.5 (NCH), 62.7 (NCH), 115.1 (d, $J_{\mathrm{C-F}}$=21 Hz, ArC), 115.7, 126.0, 127.0, 128.1, 128.7, 128.9, 131.7, 132.2, 156.4, 162.2 (d, $J_{\mathrm{C-F}}$=246 Hz, ArC), 174.5 (CO), 177.1 (CO); HRMS calcd for $\mathrm{C_{24}H_{19}FN_2O_3}$: 402.1380. Found: 402.1387.

4.5.14. 3-(4-Fluorophenyl)-5-(4-hydroxyphenyl)-2,6-dioxo-1-phenyl-1,4 diazabicyclo[3.3.0]octane (another isomer of 7b). White solid; mp 120°C; IR (KBr) 1705, 1390, 1219, 1160 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.63 (dd, J=8.4, 7.6 Hz, 1H, CH), 3.68 (dd, J=8.4, 7.6 Hz, 1H, CH), 4.78 (d, J=7.6 Hz, 1H, NCH), 5.17 (s, 1H, NCH), 6.68–7.47 (m, 13H, ArH); ^{13}C NMR (CDCl$_3$+d_6-DMSO, 68 MHz) δ 49.4 (CH), 52.1 (CH), 61.7 (NCH×2), 114.6, 114.8 (d, $J_{\mathrm{C-F}}$=22 Hz, ArC), 125.6, 127.0, 127.1, 127.5, 127.8, 128.1, 131.3, 136.8, 136.9, 156.2, 161.0 (d, $J_{\mathrm{C-F}}$=243 Hz, ArC), 173.8 (CO), 176.7 (CO); HRMS calcd for $\mathrm{C_{24}H_{19}FN_2O_3}$: 402.1380. Found: 402.1379.

4.5.15. 5-(4-Hydroxyphenyl)-3-(4-hydroxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo[3.3.0]octane (7c). Yellow solid; mp 95°C; IR (KBr) 1711, 1385, 1248, 1176 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.619–3.69 (m, 2H, CH), 3.78 (s, 3H, OMe), 4.78 (d, J=8.1 Hz, 1H, NCH), 5.11 (s, 1H, NCH), 6.86 (d, J=8.6 Hz, 2H, ArH), 7.17–7.60 (m, 11H, ArH); ^{13}C NMR (CDCl$_3$, 68 MHz) δ 49.8 (CH), 52.2 (CH), 55.1 (OMe), 60.4 (NCH), 62.5 (NCH), 114.1, 115.5, 126.0, 127.1, 128.1, 128.2, 128.8, 129.3, 131.6, 133.4, 155.6, 159.1 (ArC), 175.2 (CO), 177.5 (CO), 177.5 (CO); HRMS (**7c** and another isomer of **7c**) calcd for $\mathrm{C_{25}H_{22}N_2O_4}$: 414.1579. Found: 414.1570.

4.5.16. 5-(4-Hydroxyphenyl)-3-(4-methoxyphenyl)-2,6-dioxo-1-phenyl-1,4-diazabicyclo[3.3.0]octane (another isomer of 7c). Yellow solid; mp 178°C; IR (KBr) 1713, 1387, 1216 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.61–3.68 (m, 2H, CH), 3.84 (s, 3H, OMe), 4.76 (d, J=8.4 Hz, 1H, NCH), 5.13 (s, 1H, NCH), 6.72 (d, J=8.4 Hz, 2H, ArH), 6.95 (d, J=8.4 Hz, 2H, ArH), 7.17–7.47 (m, 9H, ArH); ^{13}C NMR (CDCl$_3$, 68 MHz) δ 49.8 (CH), 52.1 (CH), 55.3 (OMe), 61.8 (NCH), 62.4 (NCH), 113.6, 114.1, 115.2, 126.0, 127.0, 127.2, 128.2, 128.9, 129.7, 133.4, 155.2, 158.8 (ArC), 174.8, (CO), 177.3 (CO); HRMS (**7c** and another isomer of **7c**) calcd for $\mathrm{C_{25}H_{22}N_2O_4}$: 414.1579. Found: 414.1570.

4.5.17. 3-(4-Benzyloxyphenyl)-2,6-dioxo-1,5-diphenyl-1,4-diazabicyclo[3.3.0]octane (a mixture of stereoisomers 7). ^{1}H NMR (CDCl$_3$, 270 MHz) 0.3:1 mixture of stereoisomer **7** δ 2.25 (br s, 1.3H, NH), 3.58–3.74 (m, 2.6H, CH), 4.80 (d, J=6.8 Hz, 0.3H, NCH), 4.83 (d, J=7.8 Hz, 1H, NCH), 5.03 (s, 0.6H, OCH$_2$), 5.10 (s, 2H, OCH$_2$) 5.15 (s, 0.3H, NCH), 5.18 (s, 1H, NCH), 6.95 (d, J=8.6 Hz, 0.6H, ArH), 7.03 (d, J=8.4 Hz, 2H, ArH) 7.13–7.49 (m, 22.1H, ArH); ^{13}C NMR (CDCl$_3$, 68 MHz) compound **7** (major) δ 49.9 (CH), 52.4 (CH), 62.1 (NCH), 63.0 (NCH), 69.9 (OCH$_2$), 114.6, 125.8, 126.1, 127.4, 127.5, 127.5, 128.2, 128.3, 128.5, 128.9, 129.0, 130.2, 131.8, 136.8, 141.5, 158.5 (ArC), 174.5 (CO), 177.4 (CO); another isomer δ 49.9 (CH), 52.3 (CH), 62.5. (NCH), 62.7 (NCH), 70.1 (OCH$_2$), 115.1, 126.1, 127.1, 127.1, 127.4, 128.0, 128.2, 128.3, 128.5, 128.9, 131.7, 133.9, 136.6, 138.0, 158.0 (ArC), 174.4 (CO), 177.4 (CO); HRMS (mixture of stereoisomers **7**) calcd for $\mathrm{C_{31}H_{26}N_2O_3}$: 474.1943. Found: 474.1955.

4.5.18. 3,4-Dicarbomethoxy-2-(4-hydroxyphenyl)-5-phenylpyrrolidine (a mixture of stereoisomers 8 and 9). IR (KBr) 1732 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) 1.4:1 mixture of **8** and **9** (3.17 (s, 4.2H, OMe), 3.24 (2, 3H, OMe), 3.54–3.71 (m, 12H), 4.38 (d, J=8.4 Hz, 1.4H, NCH), 4.43 (d, J=8.4 Hz, 1H, NCH), 4.68 (d, J=8.4 Hz, 1H, NCH), 4.71 (d, J=8.4 Hz, 1.4H, NCH), 6.73 (d, J=8.6 Hz, 2H, ArH), 6.80 (d, J=8.1 Hz, 2.8H, ArH), 7.23–7.63 (m, 16.8H, ArH); ^{13}C NMR (CDCl$_3$, 68 MHz) **8** and **9** δ 51.5, 51.6, 52.2, 53.9, 54.6, 54.8 (OMe, CH), 64.4, 64.9, 65.7, 66.0, (NCH), 114.9, 115.4, 127.0, 127.4, 127.6, 127.9, 128.0, 128.4, 128.5, 128.7, 130.7, 132.6, 138.6, 140.7, 155.2, 155.5 (ArC), 172.7, 172.8, 173.3, 173.4 (CO); HRMS (**8** and **9**) calcd for $\mathrm{C_{20}H_{21}NO_5}$: 355.1420. Found: 355.1434.

4.5.19. 3,4-Dicarbomethoxy-2-(4-hydroxyphenyl)-5-phenylpyrrolidine (10). Stereochemistry was determined on the basis of the NOE effect between H-4 and H-5 (18%). white solid; mp 182°C; IR (KBr) 1745, 1358, 1215 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.21 (s, 3H, OMe), 3.64–3.67 (m, 2H, CH), 4.48-4.50 (m, 2H, NCH), 6.54 (d, J=8.1 Hz, 2H, ArH), 7.12–7.37 (m, 7H, ArH); ^{13}C NMR (CDCl$_3$, 68 MHz) δ 51.5 (OMe), 51.6 (OMe), 52.5 (CH), 53.2 (CH), 64.8 (NCH), 65.1 (NCH), 65.1 (NCH), 115.5, 127.0, 127.5, 128.3, 128.5, 137.3, 155.9 (ArC), 171.7 (CO), 172.0 (CO); HRMS calcd for $\mathrm{C_{20}H_{21}NO_5}$: 355.1420. Found: 355.1414.

4.5.20. 3,4-Dicarbomethoxy-2-(4-hydroxyphenyl)-5-phenylpyrrolidine (11). Stereochemistry was determined on the basis of the NOE effect between H-2 and H-3 (2%), and H-4 and H-5 (3%). white solid: mp 177°C; IR (KBr) 1747, 1347, 1215 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.16–3.31 (m, 2H, CH), 3.65 (s, 3H, OMe), 3.66 (s, 3H, OMe), 4.68 (d, J=7.3 Hz, 1H, NCH), 4.72 (d, J=7.3 Hz, 1H, NCH), 6.79–6.83 (m, 2H, ArH), 7.26–7.56 (m, 7H, ArH); ^{13}C NMR (CDCl$_3$ 68 MHz) δ 52.0 (OMe), 52.1 (OMe), 54.7 (CH), 54.8 (CH), 63.7 (NCH), 63.9 (NCH), 115.2, 127.0, 127.6, 128.3, 128.4, 133.9, 142.0, 155.0, (ArC), 172.1 (CO), 172.2 (CO); HRMS (CI) calcd for $\mathrm{C_{20}H_{22}NO_5}$: (M+H)$^{+}$: 356.1498. Found: 356.1503.

4.5.21. 3,4-Dicarbomethoxy-2-(4-hydroxyphenyl)-5-phenylpyrrole (12). Yellow liquid: IR (neat) 1716 cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 3.74 (s, 3H, OMe), 3.76 (s, 3H, OMe), 6.71 (d, J=7.3 Hz, 2H, ArH), 7.26–7.36 (m, 5H, ArH), 7.49 (d, J=8.1 Hz, 2H, ArH); ^{13}C NMR ($CDCl_3$ 68 MHz) δ 52.0 (OMe), 112.4, 113.7, 115.4, 122.4, 127.8, 128.3, 128.4, 129.5, 130.4, 133.6, 135.6, 156.3 (ArC), 166.0 (CO), 166.1 (CO); HRMS calcd for $C_{20}H_{17}NO_5$: 351.1107. Found: 351.1111.

4.5.22. 3,4-Dicarbomethoxy-1-(1,2-dicarbomethoxyethenyl)-2-(4-hydroxyphenyl)-5-phenyl pyrrole (13). Yellow solid; mp 155°C; IR (neat) 1730, 1215 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.38 (s, 3H, OMe), 3.62 (s, 3H, OMe), 3.71 (s, 3H, OMe), 3.74 (s, 3H, OMe), 5.77 (s, 1H, C=CH), 6.75 (d, J=8.6 Hz, 2H, ArH), 7.23 (d, J=8.6 Hz, 2H, ArH), 7.23 (d, J=8.6 Hz, 2H, ArH), 7.34–7.44 (m, 5H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 51.9, 52.0, 52.4, 52.8 (OMe), 114.9, 115.0, 115.3, 120.6, 127.9, 128.2, 128.9, 130.7, 132.2, 135.5, 136.2, 137.0, 156.5 (C=CH, ArC), 162.2, 163.4, 164.7, 165.0 (CO); HRMS calcd for $C_{26}H_{23}NO_9$: 493.1373. Found: 493.1366.

4.5.23. 3,4-Dicarbomethoxy-1-(1,2-dicarbomethoxyethenyl)-2-(4-hydroxyphenyl)-5-phenyl pyrrole (another isomer of 13). Yellow liquid; IR (neat) 1720, 1219 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 3.48 (s, 3H, OMe), 3.63 (s, 3H, OMe), 3.68 (s, 3H, OMe), 3.81 (s, 3H, OMe), 6.69 (d, J=8.6 Hz, 2H, ArH), 6.80 (d, J=8.4 Hz, 2H, ArH), 7.26–7.38 (m, 5H, ArH), 7.88 (s, 1H, C=CH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 51.8, 52.1, 52.4, 54.5 (OMe), 115.7, 118.9, 126.0, 127.7, 128.5, 129.2, 129.3, 130.4, 130.9, 131.5, 131.8, 143.6, 150.0 (C=CH, ArC), 157.4, 163.3, 164.7, 166.8 (CO); HRMS calcd for $C_{26}H_{23}NO_9$: 493.1373. Found: 493.1374.

4.6. Preparation of resin 16

To a column-shaped flask equipped with a filter apparatus under nitrogen were added dimethylsilylated polystyrene **14** (purchased from Novabiochem, loading level=1.73 mmol/g, 1.17 g, 2.02 mmol) and 1,3-didichloro-5,5-dimethylhydantoin (1.19 g, 6.06 mmol) in CH_2Cl_2 (20.9 mL). After 1.5 h, the mixture was filtered and washed with CH_2Cl_2 (3×10 mL) and THF (3×10 mL) and dried in vacuo to give resin **15**.

To a solution of n-BuLi (1.6 M in hexane, 6.49 mL) in THF (20 mL) was slowly added dropwise a solution of 2-(4-bromophenyl)-1,3-dioxolane (2.31 g, 10.1 mmol) in THF (40 mL) at −78°C, and stirred for 1 h. The reaction mixture was then transferred via cannula to the flask containing the fleshly prepared resin **15** (2.02 mmol) and THF (5 mL), allowed to warm slowly to room temperature, and refluxed for 1.5 h. The resin was filtered and washed sequentially with MeOH (3×20 mL), THF (3×20 mL), ad CH_2Cl_2 (3×20 mL), and dried in vacuo to give resin **16** (1.08 g); IR (KBr) 3026, 2922, 1601, 1493, 1452, 1408, 1250, 1084, 831, 766 cm^{-1}.

4.7. Preparation of resin 17

To a suspension of resin **16** (1.08 g) in THF (10 mL) was added 1N HCl (5 mL), then agitated for 24 h at room temperature. The reaction mixture was filtered and washed sequentially with DMF (2×10 mL), DMF/H_2O=1/1 (2×10 mL), MeOH (2×10 mL), CH_2Cl_2 (2×10 mL), and Et_2O (10 mL), and dried in vacuo to give resin **17** (0.93 g); IR (KBr) 3026, 2922, 1705, 1599, 1493, 1452, 1250, 1119, 1030, 698 cm^{-1}.

4.8. Preparation of polymer-supported α-silylimine 18

To a suspension of resin **17** (700 mg) in toluene (20 mL) was added α-(trimethylsilyl)benzylamine (823 mg, 4.6 mmol), and refluxed for 5.5 h under Dean–Stark condition. The reaction mixture was filtered and washed with THF (2×10 mL), CH_2Cl_2 (2×10 mL), dried in vacuo to give resin **18** (720 mg, 48% for four steps). (Yield was determined by %N analysis on the resin.) IR (KBr) 3024, 2922, 1633, 1601, 1493, 1452, 1385, 1248, 1109, 1028 cm^{-1}.

4.9. Generation and cycloaddition of azomethine ylide from resin 18 by thermal 1,2-silatropy

To a suspension of resin **18** (300 mg, 0.42 mmol) in toluene (3 mL) was added N-phenylmaleimide (289 mg, 1.66 mmol) and the mixture was heated at 180°C in a sealed tube for 6 h. after cooling to room temperature, the resin was filtered and washed sequentially with DMF (2×5 mL), MeOH (2×5 mL), CH_2Cl_2 (2×5 mL), and dried in vacuo to give the polymer-supported cycloadduct (392 mg); IR (KBr) 3026, 2922, 1720, 1601, 1493, 1452, 1377, 1109, 762 cm^{-1}.

4.9.1. 2,6-Dioxo-1,3,5-triphenyl-1,4-diazabicyclo[3.3.0]octane (19). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (15%), and H-5 and H-8 (4%). Colorless crystalline solid; mp 202–203°C; IR (KBr) 1772 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.10 (br s, 1H NH), 3.63–3.75 (m, 2H, CH), 4.87 (d, J=8.6 Hz, 1H, NCH), 5.22 (br s, 1H, NCH), 7.20–7.50 (m, 15H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 49.8 (CH), 52.3 (CH), 62.6 (NCH), 63.1 (NCH), 125.9, 126.1, 127.2, 127.6, 128.2, 128.3, 128.4, 128.9, 129.0, 131.8, 138.0, 141.6 (ArC), 174.4 (CO), 177.4 (CO); MS m/z 369 (M$^+$); Anal. calcd for $C_{24}H_{20}N_2O_2$; C, 78.24; H, 5.47; N, 7.60. Found: C, 78.03; H, 5.44; N, 7.50.

4.9.2. 2,6-Dioxo-1,3,5-triphenyl-1,4-diazabicyclo[3.3.0]octane (20 *exo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (16%). colorless plates; mp 237°C; IR (KBr) 1710 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.36 (br s, 1H, NH), 3.58 (dd, J=5.4, 2.0 Hz, 2H, CH), 4.72 (dd, J=5.4, 2.0 Hz, 2H, NCH), 7.10–7.58 (m, 15H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 49.8 (CH), 64.2 (NCH), 126.1, 127.2, 128.1, 128.3, 128.9, 131.9, 137.8 (ArC), 174.2 (CO); MS m/z 368 (M$^+$), 195; Anal. calcd for $C_{24}H_{20}N_2O_2$: C, 78.24; H, 5.47; N, 7.60. Found: C, 78.14; H, 5.38; N, 7.62.

4.9.3. 2,6-Dioxo-1,3,5-triphenyl-1,4-diazabicyclo[3.3.0]octane (20 *endo*). Stereochemistry was determined on the basis of the NOE effect between H-3 and H-7 (5%). colorless plates; mp 198°C; IR (KBr) 1710 cm^{-1}; ^{1}H NMR ($CDCl_3$, 270 MHz) δ 2.45 (br s, 1H, NH), 3.45 (dd, J=5.0, 2.0 Hz, 2H, CH), 4.54 (dd, J=5.0, 2.0 Hz, 2H, NCH), 7.31–7.71 (m, 15H, ArH); ^{13}C NMR ($CDCl_3$, 68 MHz) δ 53.6 (CH), 64.8 (NCH), 126.4, 126.9, 128.6, 128.6, 128.7, 129.1, 131.7, 141.0 (ArC), 175.8 (CO); MS m/z 368 (M^+), 195; Anal. calcd for $C_{24}H_{20}N_2O_2$: C, 78.24; H, 5.47; N, 7.60. Found: C, 78.04; H, 5.41; N, 7.52.

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