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Iodine assisted palladium catalyzed ring opening of bicyclic hydrazines with organoboronic acids: stereoselective synthesis of functionalized cyclopentenes and alkylidene cyclopentenes†

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A novel reactivity of organoboronic acids with bicyclic hydrazines leading to the stereoselective formation of *trans*-vicinal disubstituted cyclopentenes in good to excellent yield is discussed. The reaction of cyclopentadiene and fulvene derived azabicyclic alkenes with organoboronic acids afforded the *trans*-3,4-disubstituted cyclopentenes and alkylidene cyclopentenes in good to excellent yields. The products, having a broad range of substituents, are important intermediates in the synthesis of a number of pharmaceutically important molecules.

Introduction

The Suzuki reaction[1] which involves the palladium catalyzed cross-coupling of aryl and vinyl halides or triflates with boronic acids is one of the most powerful methods for carbon–carbon bond formation. This reaction has led to numerous spectacular results in synthetic organic chemistry and has been well utilized in the synthesis of a large number of organic molecules including natural products, pharmaceutical intermediates and industrially important drug molecules.[2] It has been employed in the industrial production of losartan,[3a] and in the synthesis of selective estrogen receptor agonists for central nervous system disorders.[3b] The commonly used Suzuki reactions are homocoupling of boronic acids and cross-coupling with organic halides. Aryl, alkenyl and alkynyl halides along with triflates and thioethers are considered as suitable substrates for the cross-coupling reactions.[4] This reaction has been used as an efficient method for the arylation of various *N*-containing aryls including pyrimidines and quinazolines.[5]

In the past few years, attempts have been devoted to the cross-coupling of organoboron compounds with various substrates like alkenes, alkynes, norbornene and norbornadiene. Kosugi *et al.* have shown that the Mizoroki–Heck type reaction of several organoboron reagents with these substrates occurs in aprotic solvents.[6] Even though a palladium–imidazolium carbene catalyzed reaction of aryl diazonium tetrafluoroborates was reported by Andrus *et al.*, it was confined only to substrates like styrenes and acrylates.[7] Rhodium catalyzed coupling of aryl boronic acids with oxa and aza bicyclic olefins was reported by Lautens *et al.*[8] Apart from the above mentioned reports, there are no detailed investigations on the reactivity of organoboron compounds with alkenes.

A great deal of effort has been directed at the functionalization of unsaturated cyclopentene skeletons. Along this perspective, bicyclic hydrazines have been evaluated as versatile building blocks for the synthesis of substituted cyclopentenes. Although quite a few successes have been reported in the desymmetrization of these substrates, the majority of them resulted in the formation of 3,5-disubstituted cyclopentenes.[9] 3,4-Disubstituted cyclopentenes were observed as minor products from *meso* bicyclic hydazines[10] and *N*-acyl nitroso hetero Diels–Alder adducts.[11] It is to be noted that 3,5-disubstituted cyclopentenes were formed as major products in all these transformations. As part of our program on the palladium catalyzed reactions of bicyclic hydazines, recently we have disclosed an efficient and stereoselective synthesis of *trans*-vicinal disubstituted hydrazinocyclopentenes in excellent yields *via* a one step ring opening of these substrates with organostannanes.[12] In continuation of our interest in this area, we have reported a novel reactivity of organoboronic acids with bicyclic hydrazines leading to the synthesis of substituted cyclopentenes.[13] Soon after publication of this work, Pineschi and coworkers reported a rhodium catalyzed asymmetric ring opening of bicyclic hydrazines with aryl boronic acids.[14] The present manuscript describes the details of our investigation on iodine assisted palladium catalyzed ring opening of bicyclic hydrazines (Fig. 1) with a number of organoboronic acids, along with the results of our investigation with fulvene derived bicyclic hydrazines.

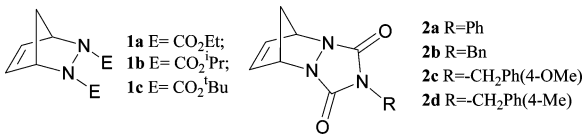

Fig. 1 Bicyclic and tricyclic hydrazines used for the study.

Results and discussion

1. Palladium catalyzed ring opening of cyclopentadiene derived azabicyclic olefins

The bicyclic hydrazines selected for our studies are shown in Fig. 1. Our experiments started with the reaction of phenyl boronic acid with the bicyclic olefin[15] **1a** in the presence of the

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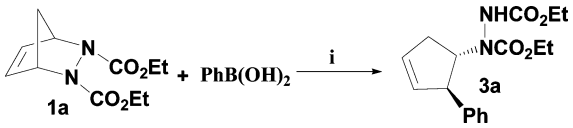
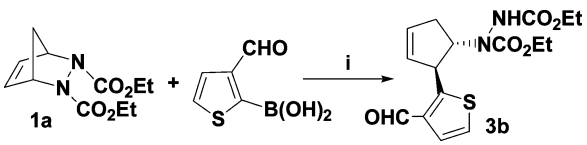
$Pd(OAc)_2$–PPh_3–I_2 catalyst system in 1 : 1 mixture of THF and H_2O. The reaction afforded 3-phenyl-4-hydrazino cyclopentene **3a** in 52% yield (Scheme 1). The structure of the compound **3a** was assigned based on the spectroscopic data and by comparison to the literature data.[12,16] In the IR spectrum the stretching vibrations of NH and CO were observed at 3294 and 1715 cm^{-1} respectively. In the ^1H NMR spectrum, the NH proton and the carboethoxy protons were seen at δ 6.53, 4.19 and 1.27 ppm respectively. The carbonyl carbons were discernible at δ 156.7 and 155.8 in the ^{13}C NMR spectrum. The structure was further confirmed by high resolution mass spectral analysis.



Scheme 1 *Reagents and conditions*: (i) $Pd(OAc)_2$, PPh_3, I_2, K_2CO_3, THF–H_2O (1 : 1), 52%.

In order to develop conditions suitable for this transformation we surveyed a number of catalysts and ligands among which $Pd(OAc)_2$–Ph_3P was found to be the best catalyst system. Further optimization studies showed that AgOTf and iodine gave comparable yields; from these we selected the readily available and cheap iodine as the Lewis acid for our studies (Table 1). The best conditions for the reaction were found to be a 1 : 2 mixture of boronic acid–olefin with 10 mol% $Pd(OAc)_2$, 20 mol% Ph_3P and 5 mol% iodine with 2.4 equiv. K_2CO_3 in 1 : 1 THF–H_2O as solvent. Under these conditions, the reaction shown in Scheme 1 afforded the product **3a** in 93% yield.

Then we turned our attention towards the reactivity of heteroaryl boronic acids in the palladium catalyzed ring opening reactions. A model reaction using 3-formyl-2-thiophene boronic acid and bicyclic alkene **1a** afforded the ring opened product **3b** in 79% yield (Scheme 2).



Scheme 2 *Reagents and conditions*: (i) $Pd(OAc)_2$, PPh_3, I_2, K_2CO_3, THF–H_2O (1 : 1), 79%.

In the course of the study we also investigated the reaction of tricyclic olefins[17] derived from triazoline dione and cyclopentadiene. These substrates also reacted in the same manner affording the substituted hydrazinocyclopentenes in good to excellent yields (Scheme 3). Tables 2 and 3 summarize the results of our investigations.

Table 1 Optimization of catalyst system[a]

Catalyst	Lewis acid	Yield (%)
$Pd(OAc)_2$	I_2	52
$PdCl_2$	I_2	26
$Pd_2(dba)_3 \cdot CHCl_3$	I_2	38
$Pd(OAc)_2$	$Sc(OTf)_3$	42
$Pd(OAc)_2$	$Yb(OTf)_3$	35
$Pd(OAc)_2$	AgOTf	55
$Pd(OAc)_2$	$Cu(OTf)_2$	30
$Pd(OAc)_2$	I_2	93[b]

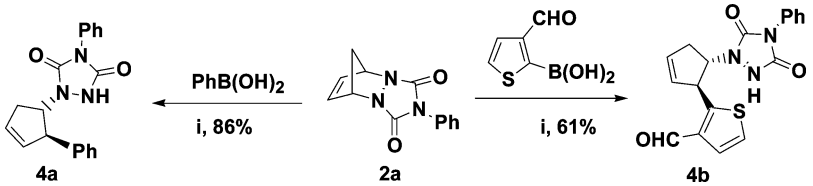
[a] Conditions: boronic acid (1 equiv.), olefin (1 equiv.), catalyst (10 mol%), PPh_3 (20 mol%), Lewis acid (5 mol%), K_2CO_3 (2.4 equiv.), THF–H_2O (1 : 1). [b] 2 equiv. of olefin were used.

Mechanism

The mechanism of the reaction was found to be similar to the one proposed for the C–N bond cleavage of bicyclic hydrazines in the palladium catalyzed reaction with organostannanes.[10,12] The catalytic cycle involves transmetalation of the aryl boronic acid to PdX_2 giving ArPdX, addition of ArPdX to C–C double bond and elimination of X–Pd–Nu along with the C–N bond cleavage. By looking at the structures of both starting material and the product, the present reaction can be viewed as going through the replacement of the allylic heteroatom by a nucleophilic carbon (from the boronic acid induced by iodine), similar to Tsuji–Trost chemistry.[18] Even though the catalytic cycles are not the same, we believe that under the reaction conditions employed, the mechanism of the reaction follows more closely the Suzuki–palladium insertion pathway. Hence the present reaction can be viewed as a modified Suzuki type reaction of the bicyclic hydrazines. The proposed mechanism is outlined in Scheme 4

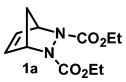
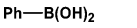
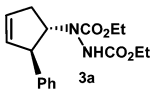
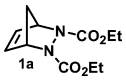
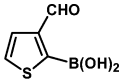
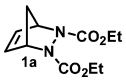
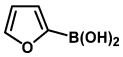
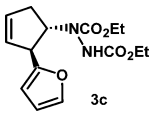
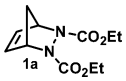
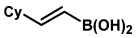
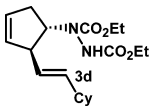
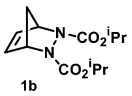
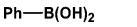
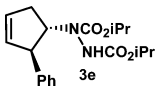
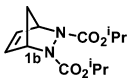
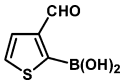
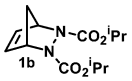
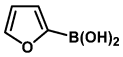
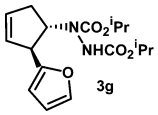
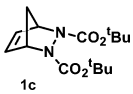
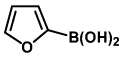
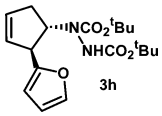
2. Palladium catalyzed ring opening of fulvene derived azabicyclic olefins

Encouraged by the studies that have been conducted on cyclopentadiene derived azabicyclic substrates, we became interested in the pentafulvene derived bicyclic hydrazines. Even though the synthesis of this type of bicyclic substrates has been reported as early as 1968,[19] there was no serious attempt to study their synthetic utility. Total synthesis of rudmollin which displays *in vivo* activity against P-388 lymphoid leukemia involves atom transfer cyclization of fulvene based bicyclic hydrazine.[20] Along this line we reported the pentafulvene derived bicyclic hydrazines to be effective substrates for the palladium catalyzed ring opening reactions with organostannanes leading to the synthesis of alkylidene cyclopentenes. This prompted us to explore the reactivity of these substrates with organoboronic acids.

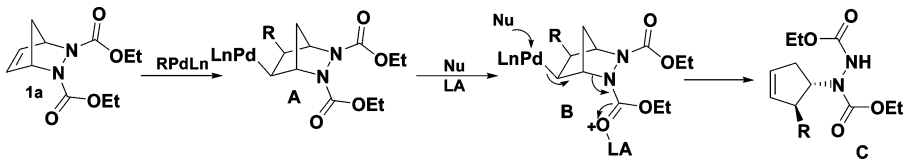


Scheme 3 *Reagents and conditions*: (i) $Pd(OAc)_2$, PPh_3, I_2, K_2CO_3, THF–H_2O (1 : 1).

Table 2 Palladium catalyzed reaction of azabicyclic olefins with boronic acids[a]

Entry	Substrate	Boronic acids	Yield (%)	Product
1			93	
2			79[b]	
3			72[b]	
4			53[b]	
5			63	
6			73[b]	
7			77[b]	
8			37[b]	

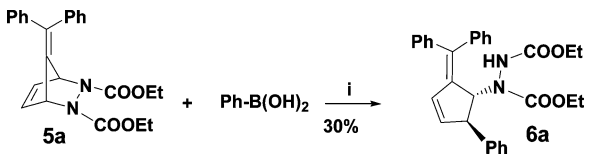
[a] Conditions: boronic acid (1 equiv.), **1a–c** (2 equiv.), $Pd(OAc)_2$ (10 mol%), PPh_3 (20 mol%), I_2 (5 mol%), K_2CO_3 (2.4 equiv.), THF–H_2O (1 : 1), 60 °C, 24 h. [b] Reaction time 36 h.



Scheme 4 Proposed mechanism of the reaction.

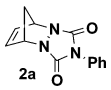
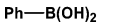
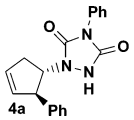
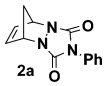
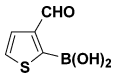
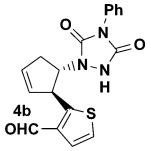
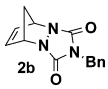
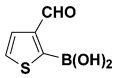
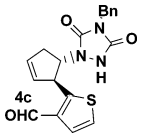
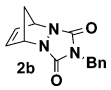
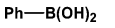
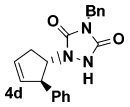
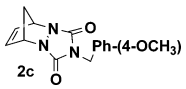
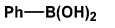
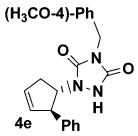
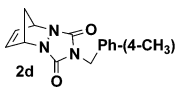
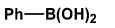
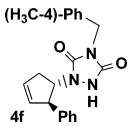
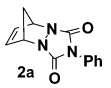
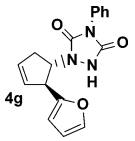
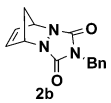
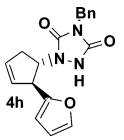
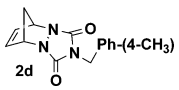
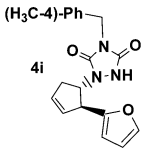
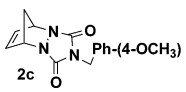
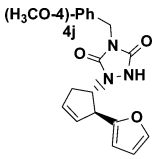
In an initial trial we carried out the reaction of phenyl boronic acid with the bicyclic olefin **5a** in the presence of the $Pd(OAc)_2$–PPh_3–I_2 catalyst system in a 1 : 1 mixture of THF and H_2O. The reaction afforded substituted alkylidene cyclopentene **6a** in 30% yield (Scheme 5). The structure of compound **6a** was assigned based on spectroscopic data and the relative configuration of the racemate was confirmed by single crystal X-ray analysis (Fig. 2).[21]

Detailed optimization studies were carried out to find out the best condition for this transformation. Our first attempt was to find out the best catalyst system. Among the different catalysts (see Table 4) screened, $PdCl_2$–dppe was found to be the best catalyst system and under these conditions **6a** was obtained in 88% yield.



Scheme 5 *Reagents and conditions*: (i) $Pd(OAc)_2$, PPh_3, I_2, K_2CO_3, THF–H_2O (1 : 1).

Table 3 Palladium-catalyzed reaction of azabicyclic olefins with boronic acids[a]

Entry	Substrate	Boronic acid	Yield (%)	Product
1			35	
2			61[b]	
3			60[b]	
4			52	
5			56	
6			40	
7			84[b]	
8			89[b]	
9			64[b]	
10			33[b]	

[a] Conditions: boronic acid (1 equiv.), **2a–d** (2 equiv.), $Pd(OAc)_2$ (10 mol%), PPh_3 (20 mol%), I_2 (5 mol%), K_2CO_3 (2.4 equiv.), THF–H_2O (1 : 1), 60 °C, 24 h. [b] Reaction time 36 h.

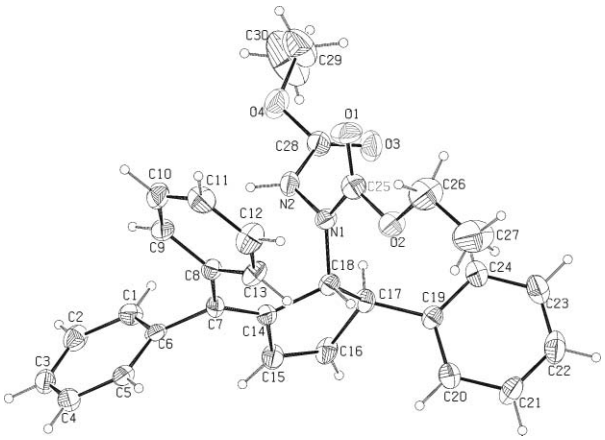


Fig. 2 ORTEP diagram of the compound **6a** (30% probability factor for the thermal ellipsoids).

Table 4 Optimization of the catalyst system[a]

Entry	Catalyst	Ligand	Lewis acid	Yield (%)
1	$Pd(OAc)_2$	PPh_3	I_2	30
2	$PdCl_2$	PPh_3	I_2	72
3	$Pd_2(dba)_3$ $CHCl_3$	PPh_3	I_2	29
4	$PdCl_2(PPh_3)_2$	PPh_3	I_2	30
5	[Pd(allyl) Cl]$_2$	PPh_3	I_2	33
6	$PdCl_2$	P(tolyl)$_3$	I_2	29
7	$PdCl_2$	P(4-F–Ph)$_3$	I_2	71
8	$PdCl_2$	P(4-OMe–Ph)$_3$	I_2	56
9	$PdCl_2$	P(4-Cl–Ph)$_3$	I_2	58
10	$PdCl_2$	dppe	I_2	88
11	$PdCl_2$	dppm	I_2	82
12	$Pd(OAc)_2$	dppe	I_2	39
13	$PdCl_2$	dppe	$Cu(OTf)_2$	21
14	$PdCl_2$	dppe	$Sn(OTf)_3$	40
15	$PdCl_2$	dppe	$Yb(OTf)_3$	43

[a] Conditions: K_2CO_3, catalyst, ligand, Lewis acid, THF–H_2O.

To extend the scope and generality of this reaction we further investigated the reactivity of heteroaryl boronic acids which also afforded substituted alkylidene cyclopentenes in good yields. Similar reactivity was observed with other bicyclic alkenes and the results obtained are summarized in Table 5.

Conclusions

In conclusion we have developed an efficient approach towards the synthesis of *trans*-vicinal disubstituted cyclopentenes and alkylidene cyclopentenes in high stereoselectivity and yield. These systems can be elaborated to potent glycosidase inhibitors and other biologically active molecules.[22] We have well demonstrated that organoboronic acids can be effectively utilized in the synthesis of functionalized cyclopentenes. In combination with our previously reported methodologies on bicyclic olefins, this methodology provides a novel process for the facile ring opening of both cyclopentadiene and pentafulvene derived bicyclic hydrazines.

Experimental section

General methods

All reactions were conducted in oven-dried glassware. Solvents used for the experiments were distilled and degassed with argon. Bicyclic hydrazines were prepared as per the literature procedures.[15,17,18] Boronic acids were purchased from Sigma Aldrich and the catalysts, ligands and Lewis acids were purchased from Alfa Aesar. All other reagents were purchased from local suppliers. All reactions were monitored by TLC (Silica gel 60 F254, 0.25 mm, Merck), visualization was effected with UV and/or by staining with Enholm yellow solution. Chromatography refers to open column chromatography on silica gel (60–120 mesh). NMR spectra were recorded at 300 (^{1}H) and 75 (^{13}C) MHz respectively on a Brüker Advance DPX-300 MHz. Chemical shifts are reported in δ (ppm) relative to TMS (^{1}H) or $CDCl_3$ (^{13}C) as internal standards. A mixture of $CDCl_3$ and CCl_4 (7 : 3) was used for recording the NMR spectra. IR spectra were recorded on a Bomem MB series FT-IR spectrometer; absorptions are reported in cm^{-1}. Mass spectra were recorded under EI-HRMS or FAB-LRMS using a JEOL JMS 600H mass spectrometer.

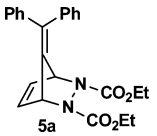
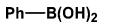
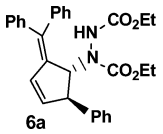
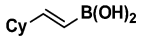
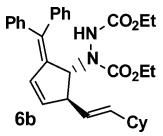
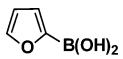
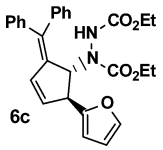
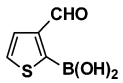
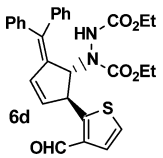
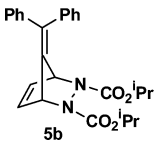
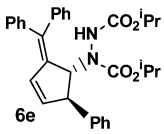
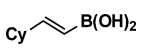
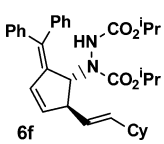
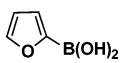
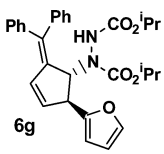
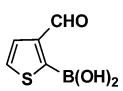
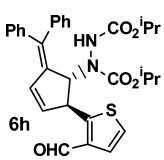
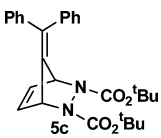
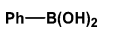
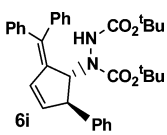
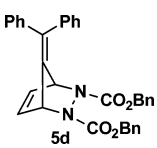
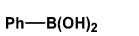
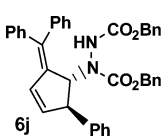
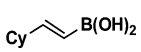
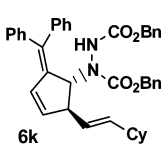
General experimental procedure for the synthesis of substituted hydrazinocyclopentenes

Bicyclic hydrazine (2 equiv.), boronic acid (1 equiv.), PPh_3 (20 mol%), $Pd(OAc)_2$ (10 mol%), I_2 (5 mol%) and K_2CO_3 (2.4 equiv.) were taken in a Schlenk tube and degassed. The mixture was dissolved in a 1 : 1 mixture of THF and H_2O (4 mL) and stirred at 60 °C for 24 h under argon atmosphere. After the completion of the reaction, the reaction mixture was diluted with dichloromethane (50 mL) and washed with water (2 × 25 mL) and saturated brine (25 mL). The organic layer was then dried over anhydrous sodium sulfate and the solvent was evaporated *in vacuo*. The residue on silica gel (60–120 mesh) column chromatography using 20% ethyl acetate in hexane afforded the product in good yield.

Compound 3a. Colorless viscous liquid. R_f 0.53 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3298, 3054, 2978, 2928, 2851, 1751, 1695, 1412, 1219, 1060, 943, 853, 757 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.30–7.13 (m, 5H), 6.64 (s, 1H), 5.87–5.84 (m, 1H), 5.71–5.68 (m, 1H), 4.74 (d, 1H, J = 6.69 Hz), 4.25–4.12 (m, 2H), 4.00 (s, 3H), 2.72–2.59 (m, 2H), 1.31–1.21 (m, 3H), 1.04 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.9, 155.9, 143.3, 132.7, 129.8, 128.4, 127.5, 126.5, 67.4, 62.3, 53.7, 35.1, 14.5, 14.2. MS (LR-FAB) [M + 1] calculated for $C_{17}H_{22}N_2O_4$: 319.1580; found 319.1608.

Compound 3b. Colorless viscous liquid. R_f 0.34 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3296, 3052, 2983, 2934, 2857, 1744, 1714, 1681, 1514, 1465, 1386, 1236, 1174, 1060, 952, 866, 760 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 9.95 (s, 1H), 7.36–7.35 (m, 1H), 7.19–7.18 (m, 1H), 6.51 (s, 1H), 5.97–5.95 (m, 1H), 5.69 (m, 1H), 5.08 (m, 1H), 4.24–4.17 (m, 4H), 3.99 (s, 1H), 2.67 (m, 2H), 1.31–1.26 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.2, 158.8, 155.8, 140.7, 132.4, 130.9, 128.1, 123.7, 63.1, 62.9, 48.0, 35.2, 14.5, 14.3. MS (LR-FAB) [M + 1] calculated for $C_{16}H_{20}N_2O_5S$: 353.1093; found 353.1114.

Table 5 Palladium catalyzed ring opening of fulvene derived bicyclic hydrazines

Entry	Substrate	Boronic acid	Product	Yield (%)
1				81
2	**5a**			60
3	**5a**			43
4	**5a**			38
5				75
6	**5b**			58
7	**5b**			30
8	**5b**			40
9				67
10				63
11	**5d**			70

Reaction conditions: boronic acid (1 equiv.), olefin (1 equiv.), $PdCl_2$ (10 mol%), dppe (10 mol%), I_2 (5 mol%), K_2CO_3 (2.4 equiv.), THF–H_2O (1 : 1)

Compound 3c. Colorless viscous liquid. R_f 0.39 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3294, 3059, 2978, 2928, 2851, 1749, 1715, 1591, 1503, 1465, 1377, 1236, 1168, 1127, 1060, 946, 866, 760, 655 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.34–7.26 (m, 1H), 6.53 (s, 1H), 6.27–6.26 (m, 1H), 6.09 (s, 1H), 5.81 (m, 1H), 5.70 (m, 1H), 4.94–4.92 (m, 1H), 4.23–4.10 (m, 5H), 2.73–2.59 (m, 2H), 1.31–1.17 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.8, 155.8, 141.4, 130.1, 128.2, 110.2, 105.1, 67.2, 62.7, 62.4, 47.7, 35.0, 14.5, 14.3. HRMS (EI) M^+ calculated for $C_{15}H_{20}N_2O_5$: 308.1372; found 308.1364.

Compound 3d. Colorless viscous liquid. R_f: 0.41 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3297, 3049, 2972, 2923, 2851, 1739, 1714, 1607, 1517, 1467, 1325, 1168, 1059, 757 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 6.37 (s, 1H), 5.66–5.65 (m, 1H), 5.54–5.52 (m, 1H), 5.43–5.40 (m, 1H), 5.38–5.27 (m, 1H), 4.57–4.55 (m, 1H), 4.21–4.12 (m, 4H), 3.65 (m, 1H), 3.29 (s, 1H), 2.55–2.46 (m, 2H), 1.69–1.66 (m, 6H), 1.40–1.21 (m, 10H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.7, 156.1, 137.5, 137.2, 132.7, 128.8, 62.4, 62.1, 50.8, 40.5, 36.8, 33.1, 31.1, 26.2, 26.2, 14.4. MS (LR-FAB) [M + 1] calculated for $C_{19}H_{30}N_2O_4$: 350.2206; found: 350.2223.

Compound 3e. Colorless viscous liquid. R_f 0.46 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3291, 3054, 2981, 2928, 2862, 1742, 1698, 1492, 1386, 1260, 1176, 1108, 1034, 954, 757, 700 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.23–7.12 (m, 5H), 6.29 (s, 1H), 5.80–5.77 (m, 1H), 5.66–5.64 (m, 1H), 4.96–4.87 (m, 1H), 4.69–4.67 (m, 2H), 3.92 (s, 1H), 2.59–2.53 (m, 2H), 1.23–1.21 (m, 12H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.5, 155.6, 143.4, 132.8, 132.2, 129.8, 128.4, 127.9, 126.5, 70.0, 69.8, 67.3, 53.7, 35.8, 22.0, 21.7. MS (LR-FAB) [M + 1] calculated for $C_{19}H_{26}N_2O_4$: 347.1893; found: 347.1895.

Compound 3f. Colorless viscous liquid. R_f: 0.42 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3303, 3082, 2981, 2928, 2857, 1736, 1698, 1514, 1467, 1374, 1238, 1177, 1107, 1047, 960, 843, 741 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 9.85 (s, 1H), 7.36–7.34 (m, 1H), 7.19–7.17 (m, 1H), 6.49 (s, 1H), 5.96–5.95 (m, 1H), 5.70–5.64 (m, 1H), 4.98–4.92 (m, 3H), 4.24–4.17 (m, 1H), 2.65 (m, 2H), 1.33–1.28 (m, 12H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.9, 158.4, 155.2, 140.6, 132.4, 131.2, 128.2, 123.6, 69.9, 65.1, 61.3, 47.9, 35.1, 21.9, 21.7. HRMS (EI) M^+ calculated for $C_{18}H_{24}N_2O_5S$: 380.1406; found: 380.1390.

Compound 3g. Colorless viscous liquid. R_f: 0.44 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3314, 3060, 2978, 2857, 1732, 1712, 1599, 1501, 1468, 1374, 1267, 1148, 1036, 762 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.32 (m, 1H), 6.61 (s, 1H), 6.25 (m, 1H), 6.08 (m, 1H), 6.00–5.85 (m, 2H), 4.96–4.94 (m, 3H), 4.15–4.08 (m, 1H), 2.65 (m, 2H), 1.28–1.24 (m, 12H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.4, 155.2, 142.1, 130.7, 128.5, 119.1, 110.5, 107.9, 63.5, 60.3, 47.0, 33.0, 22.1, 21.9, 20.9. HRMS (EI) M^+ calculated for $C_{17}H_{24}N_2O_5$: 336.1685; found: 336.1670.

Compound 3h. Colorless viscous liquid. R_f 0.57 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3302, 3065, 2956, 2918, 2846, 1767, 1732, 1619, 1503, 1462, 1322, 1251, 1159, 1027, 958, 757 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.26 (s, 1H), 6.52 (s, 1H), 6.28 (s, 1H), 6.08 (m, 1H), 5.87–5.86 (m, 1H), 5.48–5.46 (m, 1H), 4.90 (s, 1H), 4.07–4.02 (m, 1H), 2.70–2.61 (m, 2H), 1.49 (s, 18H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 155.2, 154.5, 140.6, 135.5, 128.3, 121.9, 109.6, 105.7, 82.8, 68.4, 58.3, 47.2, 37.1, 28.1. HRMS (EI) M^+ calculated for $C_{19}H_{28}N_2O_5$: 364.1998; found: 364.1912.

Compound 4a. Colorless viscous liquid. R_f 0.39 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3351, 3054, 2925, 2851, 1713, 1593, 1437, 1172, 1120, 1093, 954, 844, 722, 695 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.53 (s, 1H), 7.51–7.43 (m, 10H), 5.87–5.84 (m, 1H), 5.74–5.72 (m, 1H), 4.78–4.76 (m, 1H), 4.21–4.18 (m, 1H), 2.75–2.68 (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.4, 156.7, 142.4, 134.5, 133.2, 132.4, 131.8, 130.6, 129.7, 129.1, 128.9, 128.7, 119.6, 65.1, 53.7, 35.2. MS (LR-FAB) [M + 1] calculated for $C_{19}H_{17}N_3O_2$: 320.1321; found: 320.1364.

Compound 4b. Colorless viscous liquid. R_f 0.34 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3348, 3052, 2983, 2923, 2846, 1712, 1705, 1699, 1596, 1503, 1427, 1231, 1133, 1048, 949, 845, 768, 707, 628 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 9.94 (s, 1H), 8.52 (s, 1H), 7.50–7.34 (m, 6H), 7.23–7.22 (d, 1H, J = 5.1 Hz), 6.00 (m, 1H), 5.78 (m, 1H), 5.24 (m, 1H), 4.75–4.67 (m, 1H, J = 7.8 Hz), 2.82–2.79 (m, 1H), 2.82–2.70 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.7, 156.9, 154.6, 141.3, 136.9, 132.0, 131.6, 131.1, 130.6, 129.3, 125.8, 66.7, 46.7, 34.5. HRMS (EI) M^+ calculated for $C_{18}H_{15}N_3O_3S$: 353.0834; found: 353.0822.

Compound 4c. Colorless viscous liquid. R_f 0.32 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3346, 3054, 2989, 2917, 2846, 1714, 1704, 1694, 1549, 1448, 1355, 1231, 1152, 1070, 952, 823, 765, 729, 696 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 9.87 (s, 1H), 8.51 (s, 1H), 7.39–7.22 (m, 7H), 5.98 (m, 1H), 5.75 (m, 1H), 5.18–5.15 (d, 1H, J = 8.4 Hz), 4.69–4.55 (m, 3H), 2.72–2.59 (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.9, 156.9, 155.6, 136.9, 135.7, 131.9, 131.6, 130.7, 128.9, 128.9, 124.6, 67.3, 46.4, 43.2, 34.1. MS (LR-FAB) [M + 1] calculated for $C_{19}H_{17}N_3O_3S$: 368.0991; found: 368.1003.

Compound 4d. Colorless viscous liquid. R_f 0.38 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3341, 3060, 2917, 2846, 1710, 1694, 1604, 1489, 1454, 1360, 1253, 1157, 1070, 986, 952, 821, 760, 696 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.54 (s, 1H), 7.39–7.21 (m, 10H), 5.93–5.91 (m, 1H), 5.81–5.80 (m, 1H), 4.69–4.64 (m, 3H), 3.96–3.95 (m, 1H), 2.80–2.79 (m, 1H), 2.52–2.49 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 155.3, 153.8, 141.8, 135.8, 133.1, 129.8, 129.0, 128.9, 128.4, 127.6, 127.4, 126.6, 64.8, 54.6, 43.3, 35.5. HRMS (EI) M^+ calculated for $C_{20}H_{19}N_3O_2$: 333.1477; found: 333.1463.

Compound 4e. Colorless viscous liquid. R_f 0.59 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3347, 3061, 2956, 2920, 2851, 1711, 1694, 1610, 1575, 1455, 1355, 1297, 1249, 1028, 949, 842, 733 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.33–7.11 (m, 9H), 5.94–5.91 (m, 1H), 5.81–5.79 (m, 1H), 4.68–4.66 (m, 1H), 4.58 (s, 2H), 3.96–3.94 (m, 1H), 3.77 (s, 3H), 2.51–2.49 (m, 1H), 2.16 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 155.1, 153.6, 141.7, 132.9, 130.3, 129.6, 128.8, 128.2, 127.8, 127.3, 127.1, 126.1, 114.1, 64.5, 55.2, 54.3, 42.5, 35.3. MS (LR-FAB) [M + 1] calculated for $C_{21}H_{21}N_3O_3$: 364.1583; found: 364.1610.

Compound 4f. Colorless viscous liquid. R_f 0.37 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3346, 3054, 2917, 2857, 1705, 1591, 1514, 1448, 1250, 1168, 1028, 953, 721 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.55 (s, 1H), 7.68–7.43 (m, 9H), 5.85–5.83 (m, 1H), 5.71 (s, 1H), 4.67–4.62 (m, 1H), 4.55 (s, 2H), 4.05 (s, 1H), 2.69–2.55 (m, 2H), 2.31 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 154.8, 153.9, 142.1, 137.5, 132.8, 132.2, 132.1, 132.0, 131.9, 131.7, 129.3,

128.7, 128.6, 128.1, 64.7, 53.8, 42.5, 35.1, 21.2. HRMS (EI) M^+ calculated for $C_{21}H_{21}N_3O_2$: 347.1634; found: 347.1639.

Compound 4g. Colorless viscous liquid. R_f 0.34 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3349, 3053, 2983, 2923, 2851, 1705, 1643, 1596, 1426, 1270, 1179, 1080, 965, 795, 743, 713 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.55 (s, 1H), 7.48–7.46 (m, 5H), 7.36–7.33 (m, 1H), 6.28 (m, 1H), 6.09 (m, 1H), 5.89 (m, 1H), 5.81 (m, 1H), 4.96–4.93 (m, 1H), 4.15 (s, 1H), 2.84–2.81 (m, 1H), 2.60 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 154.2, 153.8, 142.1, 130.2, 129.1, 128.2, 126.8, 124.0, 119.2, 113.4, 110.1, 105.0, 61.5, 47.7, 35.3. HRMS (EI) M^+ calculated for $C_{17}H_{15}N_3O_3$: 309.1113; found: 309.1117.

Compound 4h. Colorless viscous liquid. R_f 0.37 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3351, 3049, 2988, 2925, 2857, 1705, 1693, 1604, 1585, 1495, 1454, 1358, 1231, 1119, 1073, 946, 781, 732, 633 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.54 (s, 1H), 7.38–7.24 (m, 6H), 6.26–6.22 (m, 1H), 6.01 (d, 1H, J = 3.3 Hz), 5.86–5.83 (m, 1H), 5.76–5.74 (m, 1H), 4.89–4.82 (m, 1H), 4.65 (s, 2H), 4.08 (m, 1H), 2.83–2.75 (m, 1H), 2.53–2.45 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 155.1, 154.3, 141.9, 135.4, 130.1, 129.9, 129.0, 125.0, 124.6, 119.2, 110.3, 64.6, 47.3, 42.9, 35.2. HRMS (EI) M^+ calculated for $C_{18}H_{17}N_3O_3$: 323.1270; found: 323.1254.

Compound 4i. Colorless viscous liquid. R_f 0.35 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3348, 3051, 2925, 2855, 1770, 1711, 1692, 1456, 1182, 784, 735 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.57 (s, 1H), 7.30–7.26 (m, 3H), 7.13–7.08 (m, 2H), 6.26 (s, 1H), 6.03–6.02 (d, 1H, J = 2.61 Hz), 5.88–5.86 (m, 1H), 5.77–5.71 (m, 1H), 4.89–4.83 (m, 1H), 4.62 (m, 2H), 4.11–4.06 (m, 1H), 2.71–2.63 (m, 2H), 2.32 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 155.3, 154.5, 142.1, 131.3, 130.2, 129.5, 128.8, 128.4, 124.6, 115.9, 110.4, 106.9, 64.8, 47.6, 42.9, 35.4, 22.9. HRMS (EI) M^+ calculated for $C_{19}H_{19}N_3O_3$: 337.1426; found: 337.1422.

Compound 4j. Colorless viscous liquid. R_f 0.56 (6 : 4 hexane–EtOAc). IR (neat) ν_{max}: 3350, 3048, 2926, 2851, 1704, 1698, 1613, 1514, 1456, 1249, 951, 842, 732 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 8.56 (s, 1H), 7.37–7.27 (m, 3H), 7.21–7.19 (m, 2H), 6.2–6.19 (m, 1H), 5.96–5.95 (d, 1H, J = 3.3 Hz), 5.81 (m, 1H), 5.72 (m, 1H), 4.8–4.77 (m, 1H), 4.54 (s, 2H), 4.03–4.0 (m, 1H), 3.72 (s, 3H), 2.72 (m, 1H), 2.43 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 154.9, 153.9, 141.9, 130.2, 130.1, 130.0, 129.1, 128.4, 124.3, 114.0, 110.3, 105.5, 61.5, 55.3, 47.6, 42.5, 35.2. HRMS (EI) M^+ calculated for $C_{19}H_{19}N_3O_4$: 353.1376; found: 353.1355.

General experimental procedure for the synthesis of alkylidene cyclopentenes

Bicyclic hydrazine (1 equiv.), boronic acid (1 equiv.), dppe (10 mol%), $PdCl_2$ (10 mol%), I_2 (5 mol%) and K_2CO_3 (2.4 equiv.) were taken in a Schlenk tube and degassed. The mixture was dissolved in a 1 : 1 mixture of THF and H_2O (4 mL) and stirred at 60 °C for 24 h under argon atmosphere. After completion of the reaction, the reaction mixture was diluted with dichloromethane (50 mL) and washed with water (2 × 25 mL) and saturated brine (25 mL). The organic layer was then dried over anhydrous sodium sulfate and the solvent was evaporated *in vacuo*. The residue on silica gel (60–120 mesh) column chromatography using 20% ethyl acetate in hexane afforded the product in good yield.

Compound 6a. White crystalline solid. Mp 136 °C. R_f 0.40 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3362, 2980, 2924, 1753, 1717, 1596, 1487, 1407, 1382, 1298, 1221, 1122, 1056, 1028, 756, 701 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.39–7.19 (m, 15H), 6.53 (s, 1H), 6.15 (dd, J_1 = 2.0 Hz, J_2 = 5.8 Hz, 1H), 5.78–5.40 (m, 2H), 4.49–4.46 (m, 1H), 4.20–4.15 (m, 2H), 3.85–3.68 (m, 2H), 1.25 (t, J = 6.6 Hz, 3H), 1.00–0.88 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.0, 154.9, 143.5, 142.4, 141.3, 140.2, 139.9, 135.2, 134.8, 133.3, 130.0, 129.6, 128.6, 128.2, 127.8, 127.6, 127.3, 126.8, 115.4, 70.0, 63.1, 62.1, 55.3, 14.4, 14.2. HRMS (EI) : M^+ calculated for $C_{30}H_{30}N_2O_4$: 482.2206; found: 482.2210.

Compound 6b. Light brown viscous liquid. R_f 0.49 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3368, 2924, 2851, 1756, 1717, 1597, 1487, 1409, 1380, 1300, 1218, 1125, 1059, 968, 756, 701 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.27–7.13 (m, 12H), 6.33 (s, 1H), 6.00 (s, 1H), 5.66–5.47 (m, 3H), 4.23–4.03 (m, 2H), 3.89–3.76 (m, 2H), 1.94 (m, 1H), 1.72–1.62 (m, 6H), 1.27–1.02 (m, 10H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.7, 155.4, 141.6, 140.6, 137.7, 132.2, 130.2, 128.7, 128.2, 128.0, 127.2, 126.8, 124.3, 124.0, 121.8, 110.5, 69.1, 62.1, 52.5, 40.8, 33.2, 32.4, 26.4, 26.1, 14.7. HRMS (EI): M^+ calculated for $C_{32}H_{38}N_2O_4$: 514.2832; found: 514.2848.

Compound 6c. Light brown viscous liquid. R_f 0.36 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3362, 2925, 2852, 1753, 1716, 1597, 1487, 1409, 1380, 1284, 1222, 1124, 1060, 919, 757, 702 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.35–7.16 (m, 12H), 6.49–6.46 (m, 1H), 6.29 (s, 1H), 6.26–6.11 (m, 2H), 5.68–5.50 (m, 1H), 4.51 (m, 1H), 4.17–4.13 (m, 2H), 3.96–3.78 (m, 2H), 1.28–1.24 (m, 3H), 1.09–0.98 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 158.7, 154.1, 141.8, 141.7, 137.2, 136.7, 136.5, 135.7, 135.6, 133.7, 133.1, 129.8, 129.6, 128.7, 128.5, 128.2, 128.1, 127.7, 110.3, 78.4, 63.2, 62.2, 55.3, 49.2, 14.3. HRMS (EI): M^+ calculated for $C_{28}H_{28}N_2O_5$: 472.1998; found: 472.1926.

Compound 6d. Light brown viscous liquid. R_f 0.24 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3368, 3291, 2982, 1716, 1671, 1596, 1487, 1405, 1383, 1298, 1233, 1124, 1057, 754, 702 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 10.28 (s, 1H), 7.38–7.16 (m, 12H), 6.61 (dd, J_1 = 4.6 Hz, J_2 = 17.7 Hz, 1H), 6.15 (s, 1H), 5.91–5.71 (m, 2H), 5.50–5.42 (m, 1H), 4.21–4.18 (m, 2H), 3.86–3.71 (m, 2H), 1.29–1.25 (m, 3H), 1.05–0.96 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.6, 156.2, 154.4, 141.3, 140.7, 139.5, 137.6, 137.2, 134.3, 129.8, 129.7, 128.7, 128.2, 127.6, 126.7, 123.8, 113.8, 70.6, 62.5, 62.0, 49.0, 14.3. MS (LR-FAB): m/z calculated for $C_{29}H_{28}N_2O_5S$: 516.1719; found: 539.05 (M + Na^+).

Compound 6e Colorless. Viscous liquid. R_f 0.49 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3362, 2981, 1750, 1721, 1599, 1471, 1401, 1300, 1247, 1177, 1108, 1029, 957, 756, 701 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$): δ 7.41–7.18 (m, 15H), 6.51 (dd, J_1 = 2.2 Hz, J_2 = 6.1 Hz, 1H), 6.16–6.11 (m, 1H), 5.73–5.41 (m, 2H), 4.96–4.93 (m, 1H), 4.55–4.40 (m, 2H), 1.30–1.25 (m, 6H), 1.06–0.76 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.3, 155.3, 140.6, 139.0, 134.7, 134.2, 133.7, 133.2, 130.0, 128.5, 128.1, 127.9, 127.7, 127.1, 126.8, 69.8, 69.1, 61.6, 55.3, 22.1, 21.5. HRMS (EI): M^+ calculated for $C_{32}H_{34}N_2O_4$: 510.2519; found: 510.2537.

Compound 6f. Light yellow viscous liquid. R_f 0.58 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3362, 2924, 2852, 1747, 1716, 1597, 1469, 1385, 1300, 1181, 1110, 1028, 966, 756, 701 cm^{-1}. ^1H NMR

(300 MHz, $CDCl_3$): δ 7.35–7.10 (m, 10H), 6.31 (d, $J = 5.5$ Hz, 1H), 6.02–6.01 (m, 1H), 5.53–5.41 (m, 3H), 4.95–4.85 (m, 1H), 4.74–4.57 (m, 1H), 4.50 (bs, 1H), 1.94 (bs, 1H), 1.73–1.69 (m, 6H), 1.33–1.05 (m, 11H), 0.96–0.88 (m, 5H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.7, 155.5, 141.5, 140.3, 137.3, 132.2, 130.0, 129.8, 129.7, 129.0, 128.4, 127.9, 127.3, 126.9, 124.4, 124.0, 119.2, 114.3, 70.3, 69.8, 66.5, 52.4, 40.8, 33.0, 31.9, 30.3, 26.5, 26.3, 22.7, 22.1. HRMS (EI): M^+ calculated for $C_{34}H_{42}N_2O_4$: 542.3145; found: 542.3154.

Compound 6g. Brownish yellow viscous liquid. R_f 0.47 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3368, 2981, 2934, 1750, 1715, 1597, 1443, 1385, 1298, 1227, 1178, 1108, 1031, 957, 756, 701, 598 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.35–7.19 (m, 12H), 6.46–6.44 (m, 1H), 6.30–6.21 (m, 2H), 6.13–6.00 (m, 1H), 5.77–5.53 (m, 2H), 4.89 (m, 1H), 4.61–4.56 (m, 1H), 1.24–0.86 (m, 12H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.1, 155.3, 141.5, 140.8, 137.2, 136.9, 136.5, 135.2, 132.9, 132.1, 130.2, 129.9, 128.2, 127.9, 127.7, 127.5, 127.3, 127.1, 126.8, 110.2, 105.3, 70.1, 69.8, 64.4, 49.5, 22.6, 21.9. MS (LR-FAB): m/z calculated for $C_{30}H_{32}N_2O_5$: 500.2311; found: 523.35 (M + Na$^+$).

Compound 6h. Yellow viscous liquid. R_f 0.33 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3368, 2978, 2928, 1716, 1682, 1597, 1468, 1386, 1314, 1234, 1179, 1105, 1028, 754, 702 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 10.29 (s, 1H), 7.47–7.16 (m, 12H), 6.62 (d, $J = 5.0$ Hz, 1H), 6.15–6.13 (m, 1H), 5.75 (m, 1H), 5.62–5.42 (m, 2H), 4.93 (m, 1H), 4.54 (m, 1H), 1.28–1.21 (m, 6H), 1.06–0.91 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.2, 156.1, 154.0, 141.6, 140.8, 136.2, 135.7, 133.6, 133.0, 129.8, 129.6, 128.9, 128.7, 128.5, 128.4, 128.2, 128.0, 127.6, 127.5, 127.4, 127.0, 70.9, 70.2, 66.3, 48.6, 21.8, 21.7. MS (LR-FAB): m/z calculated for $C_{31}H_{32}N_2O_5S$: 544.2032; found: 567.47 (M + Na$^+$).

Compound 6i. Brownish yellow viscous liquid. R_f 0.58 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3362, 2979, 1748, 1714, 1599, 1478, 1368, 1248, 1155, 944, 853, 756, 701 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.46–7.16 (m, 15H), 6.51 (d, $J = 4.3$ Hz, 1H), 6.18–6.12 (m, 1H), 5.66–5.35 (m, 2H), 4.51–4.43 (m, 1H), 1.67–1.08 (m, 18H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.0, 157.0, 154.9, 142.4, 140.0, 138.0, 136.9, 133.4, 131.7, 130.0, 128.3, 128.0, 127.7, 127.0, 126.5, 117.9, 81.0, 64.6, 54.9, 30.7, 28.6, 28.3. HRMS (EI): M^+ calculated for $C_{34}H_{38}N_2O_4$: 538.2832; found: 538.2870.

Compound 6j. Colorless viscous liquid. R_f 0.49 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3363, 2958, 1750, 1722, 1599, 1491, 1457, 1405, 1292, 1265, 1216, 1130, 1029, 850, 739, 700 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.38–7.16 (m, 25H), 6.82 (s, 1H), 6.53 (s, 1H), 6.17–6.01 (m, 1H), 5.52 (bs, 1H), 5.19–5.04 (m, 2H), 4.90–4.84 (m, 1H), 4.66 (m, 1H), 4.51 (s, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 157.2, 154.1, 140.5, 137.8, 135.8, 132.2, 130.2, 129.9, 128.8, 128.5, 128.2, 128.1, 127.6, 127.4, 124.2, 111.3, 76.8, 70.3, 67.9, 68.1. HRMS (EI): M^+ calculated for $C_{40}H_{34}N_2O_4$: 606.2519; found: 606.2532.

Compound 6k. Light brown viscous liquid. R_f 0.55 (3 : 1 hexane–EtOAc). IR (neat) ν_{max}: 3363, 3060, 2924, 2851, 1753, 1722, 1597, 1490, 1446, 1406, 1298, 1259, 1215, 1128, 1043, 971, 922, 754, 699 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.36–7.16 (m, 20H), 6.32 (s, 1H), 6.04–5.89 (m, 2H), 5.57 (m, 2H), 5.13–5.04 (m, 3H), 4.92–4.72 (m, 2H), 2.03–1.60 (m, 5H), 1.33–0.88 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 156.3, 153.2, 140.5, 137.8, 135.9, 132.2, 130.1, 129.9, 128.7, 128.6, 128.2, 128.1, 127.9, 127.3, 124.9, 116.1, 68.3, 68.1, 68.0, 52.6, 40.8, 32.1, 31.0, 30.5, 26.6, 26.3, 22.9. HRMS (EI): M^+ calculated for $C_{42}H_{42}N_2O_4$: 638.3145; found: 638.3174.

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Notes and references

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21 CCDC 640116†, Empirical formula = $C_{30}H_{30}N_2O_4$; formula weight = 482.56; temperature = 293(2) K; wavelength = 0.71073 Å; crystal system = triclinic, space group = *P*-1; unit cell dimensions = a = 8.401(2) Å, α = 95.410(4)°, b = 10.368(3) Å, β = 95.198(6)°; c = 15.647(4) Å, γ = 102.676(5)°, volume = 1315.0(6) Å^3; Z = 2, density (calculated) = 1.219 Mg m^{-3}; absorption coefficient = 0.081 mm^{-1}, F(000); 512, crystal size = 0.24 × 0.16 × 0.09 mm; theta range for data collection = 1.32 to 22.50°; index ranges = $-9 \leq h \leq 8$, $-11 \leq k \leq 11$, $-16 \leq l \leq 16$; reflections collected = 7605; independent reflections = 3428 [R_{int} = 0.0828], absorption correction = SADABS; refinement method, full-matrix least-squares on F^2, data/restraints/parameters = 3428/0/327; goodness-of-fit on F^2 = 1.001; final R indices [$I > 2\sigma(I)$] = $R1$ = 0.0724, w$R2$ = 0.1485, R indices (all data) $R1$ = 0.1930, w$R2$ = 0.2136, largest diff. peak and hole = 0.299 and −0.167 e A^{-3}.

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