Syntheses of Pyrazine-, Quinoxaline-, and Imidazole-Fused Pyrroline Nitroxides

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Dedicated to the memory of Prof. Kálmán Hideg

Abstract  
A synthesis of a new diamagnetic synthon, 1-methoxy-2,2,5,5-tetramethylpyrrolidine-3,4-dione, was developed. Condensation of this compound with aliphatic or aromatic 1,2-diamines followed by deprotection yielded pyrroline nitroxide-fused pyrazines, pteridines, or quinoxalines, demonstrated on 7 examples in 15–39% overall yield over 2 or 3 steps. Reaction of the diamagnetic 1,2-diketone with an aldehyde and ammonium acetate produced a pyrrolo[3,4-d]imidazole scaffold in the Debus–Radziszewski reaction.

Key words  
free radicals, CH functionalization, oxidation, pyrazines, protecting groups

One of the main groups of long-lived stable radicals is the nitroxide (aminoxyl) radicals. Extensive studies of stable nitroxide free radicals first appeared 60 years ago, and their application is rather diverse and extends beyond spin labeling. They are used as co-oxidants in organic chemistry, building blocks for magnetic materials, superoxide dismutase mimics, antiproliferative compounds, mediators of polymerization, redox active materials in batteries, and magnetic resonance imaging (MRI) as well as electron paramagnetic resonance imaging (EPR) contrast agents. These applications demand various scaffolds with diverse substitution patterns on pyrroline and piperidine nitroxides, including condensation with miscellaneous carbocycles and heterocycles. Synthesis of pyrroline nitroxide-fused carbocycles and heterocycles is one of the main activities of our laboratory, such as the synthesis of pyridazine- and pyrimidine-fused nitroxides (Figure 1). The latter was used in environmental studies investigating the distribution of sulfadiazine in a humic acid model system.

Until now, we could not find a method for the synthesis of pyrazine (1,4-diazine)-fused pyrroline nitroxide. Pyrazines are important structural motifs of many biologically active molecules, such as riboflavin, and drugs such as pyrazinamide (antituberculotics) and varenicline (stop-smoking drug) (Figure 2).

It was obvious that the condensation of 1,2-diamines with paramagnetic 1,2-diketones suggests a synthetic route to novel paramagnetic 1,4-diazines and quinoxalines. Inspired by the work of Sandris and Ourisson, we attempted the synthesis of 1-oxyl-2,2,5,5-tetramethylpyrrolidine-3,4-dione by SeO2 oxidation of 1-oxyl-2,2,5,5-tetramethylpyrrolidine-3-one (1) (Scheme 1); however, no reaction occurred, and only starting material was recovered.

Based on our previous findings regarding sluggish reactions, we proposed that the free radical moiety must be protected; however, neither the N–OAc protection nor the hydroxylamine HCl salt form was sufficient for camouflaging...
the nitroxide moiety in the oxidation reaction with SeO₂. For nitroxide protection, we used the O-methylation technique by a Fenton reaction in the presence of DMSO, which was worked out in Bottle’s group.¹⁹a Treatment of compound 1 with a methyl radical generating system (Fe²⁺ and aq H₂O₂ mixture in DMSO) yielded compound 2, which could be oxidized smoothly by refluxing with 1.5 equivalents of SeO₂ in AcOH to afford compound 3 in a 63% yield over two steps (Scheme 2). Deprotection of compound 3 with 3-chloroperbenzoic acid (m-CPBA)¹⁹b gave an unstable five-membered diketo nitroxide compound, which decomposed during purification.

Alternatively, we returned to the Sandris and Ourisson method, but instead of an N-acetyl derivative, the NH functionality was protected with a readily hydrolyzable trifluoroacety group,²⁰ and thus, compound 4²¹ was treated with trifluoroacetic anhydride to give compound 5 in an 82% yield. Compound 5 could also be oxidized to diketo compound 6 in a 65% yield with SeO₂ in AcOH, but it was unstable and the crude product was used immediately in the next step. The diketo compounds 3 and 6 were condensed with 1,2-diaminobenzene (7a) to furnish pyrrolo[3,4-b]quinoxalines 7b and 8, respectively. Treatment of compound 7b with m-CPBA in dichloromethane (DCM) yielded nitroxide 7c. Compound 7c was also available via hydrolysis of compound 8 with aqueous KOH in EtOH, which produced compound 9 with prolonged reaction time and in a low (32%) yield. Compound 9 was then oxidized with m-CPBA in DCM to furnish 7c in a 13% yield over three steps (Scheme 3).

Considering the instability of the diketo compound 6 and the fact that the deprotection of the sterically hindered trifluoroacetamido group required harsh basic conditions, which is not compatible with many functional groups and its troublesome application (reduction of nitroxide, trifluoroacetylation, oxidation, condensation, hydrolysis of the trifluoroacetyl group, and restoring nitroxide function), in the following work, we used the O-methylation procedure, followed by oxidation, condensation, and mild deprotection with m-CPBA. Thus, we preferred compound 3 as the main building block instead of compound 6. In analogous reactions, compound 3 was condensed with different aromatic and heteroaromatic 1,2-diamino compounds such as 2,3-diaminobenzamide (10a),²² 1,2,4,5-tetraaminobenzene (11a), 4,5-diaminopyrimidine (12a), 5,6-diaminouracil (13a) in ethanol, glacial acetic acid, or aqueous methanol to give the pyrazine ring condensed polycyclic compounds 10b, 11b, 12b, and 13b, respectively. Deprotection of 10b with m-CPBA gave the paramagnetic 5-carboxamidoquinoxaline 10c, which can be regarded as a potential poly (ADP-ribose) polymerase (PARP) inhibitor,²³ and deprotection of compound 11b offered the rigid biradical compound 11c giving a quintet line in the EPR spectrum [see the Supporting Information (SI)]. Deprotection of compound 12b furnished the paramagnetic pteridine 12c, and deprotection of compound 13b offered the paramagnetic pteridine-2,4(3H,8H)-dione 13c, the spin-labeled (SL) lumazine (Table 1).

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**Scheme 1** Attempted synthesis of a paramagnetic diketone

**Scheme 2** Synthesis of precursors of 1-oxyl-2,2,5,5-tetramethylpyrroloidine-3,4-dione

**Scheme 3** Synthesis of diamagnetic and paramagnetic pyrrolo[3,4-b]quinoxaline scaffolds
Table 1  Synthesis of Pyrazine Condensed Paramagnetic Polycyclic Compounds

<table>
<thead>
<tr>
<th>Entry</th>
<th>1,2-Diamino compound</th>
<th>Diamagnetic product</th>
<th>Paramagnetic product</th>
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*Reflex in AcOH.

To construct the pyrrolo[3,4-b]pyrazine scaffold, compound 3 was condensed with 1,2-diaminoethane (14) yielding compound 15. Aromatization of 15 by treatment with 2.0 equivalents of sodium ethoxide in methanol at reflux temperature24 followed by standing overnight yielded the pyrazine-condensed precursor 16, which was deprotected with m-CPBA to give compound 17 in a 30% yield over three steps. Upon prolonged reaction time and excess m-CPBA (5.0 equiv) the formation of N-oxide 18 was observed, which could be arylated at the C2-position by palladium catalysis25 with benzene as a reaction solvent to give compound 19 in a 38% yield (Scheme 4).

To achieve the paramagnetic analogue of the antitubercular drug pyrazinamide,26 a condensation reaction of compound 3 was conducted with ethyl 2,3-diaminopropionic acid HCl salt 2027 in EtOH with 4.0 equivalents of sodium...
ethoxide to furnish compound 21. Its hydrolysis with NaOH to the carboxylic acid and the treatment of the crude product with 1,1’-carbonyldimidazole (CDI) in THF followed by treatment with aqueous 25% ammonia gave amide 22. Treatment of compound 22 with m-CPBA gave the spin-labeled analogue 23 of pyrazinamidine in an 11% overall yield over four steps (Scheme 5).

In order to extend the scope of utilization of compound 3, we tested it in a multicomponent Debus–Radziszewski imidazole formation with modification of the Fallah and Mokhtary method utilizing tin oxide nanoparticles as catalysts. Therefore, compound 3, benzaldehyde (24), and ammonium acetate in the presence of SnO2 nanoparticles were heated at reflux temperature for 3 hours in EtOH. After the isolation of compound 25 in a 75% yield, we attempted the deprotection to nitroxide with m-CPBA, but the formation of (4,4,6,6-tetramethyl-2-phenyl-4,6-dihydropyrrolo[3,4-d]imidazol-5-yl)oxadanyl was not observed. Considering, that Chalmers et al. reported a similar deprotection on N-substituted imidazole containing scaffolds, we decided on the protection of the imidazole NH by alkylation. Therefore, treatment of 25 with Mel in THF in the presence of NaH furnished compound 26, which can be deprotected to afford 1-methylimidazole-fused pyrroline nitroxide 27 in 44% yield in two steps (Scheme 6).

In conclusion, we have developed access to 1-methoxy-2,2,5,5-tetramethylpyrroolidine-3,4-dione nitroxide precursor 3, which could be condensed with 1,2-diamines to give various quinoxalines, pyrazines, and pteridines fused with the pyrroline nitroxide precursor. The nitroxide functionality was restored by treatment of the NOMe moiety with m-CPBA. Compound 3 also was used in 1-substituted imidazole-fused pyrroline nitroxide synthesis, as the m-CPBA deprotection cannot be conducted seemingly in the presence of the imidazole NH functional group.

We hope that compound 3, as a universal building block, can be used for the synthesis of further pyrroline nitroxide-fused structures. The evaluation of further possibilities as well as biological study of newly synthesized pyrazine derivatives are in progress in our laboratory.

Melting points were determined with a Boetius micro-melting point apparatus and are uncorrected. Elemental analyses (C, H, N, and S) were performed with a Fisons EA 1110 CHNS elemental analyzer. Mass spectra were recorded on a ThermoQuest autoMass Multi spectrometer. NMR spectra were recorded on a Bruker Avance III Ascend 500 spectrometer; chemical shifts are referenced to TMS. The paramagnetic compounds were reduced to N-hydroxylamines with five equivalents of hydrazobenzene (DPPH)/radicals in situ in the NMR tube. Measurements were performed at a probe temperature 298 K in CDCl3 or DMSO-d6 or CD2OD solution. ESR spectra were recorded on Miniscope MS 200 in CHCl3 solution. All monoradicals gave a triplet line at $a_H = 14.5$ G, biradical 11c gave a quintet line at $a_H = 7.3$ G. IR spectra were recorded with a Bruker Alpha FT-IR instrument with ATR support (ZnSe plate). Flash column chromatography was performed on Merck Kieselgel 60 (0.040–0.063 mm). Compounds 1, 4, 10a, 22, and 20 were prepared as described previously. Compounds 7a, 10a–13a, 14, 24 and other reagents were purchased from Merck, Alfa Aesar, and TCI.

**Scheme 5** Synthesis of paramagnetic pyrazinamidine

**Scheme 6** Synthesis of diamagnetic and paramagnetic 1-methyl-2-phenyl-4,6-dihydropyrrolo[3,4-d]imidazole scaffold

1-Methoxyl-2,2,5,5-tetramethylpyrroloidine-3-one (2)

To a stirred solution of 1 (1.56 g, 10.0 mmol) and FeSO4·7H2O (6.9 g, 25.0 mmol) in DMSO (30 mL) at 0 °C was added 30% aq H2O2 (5 mL) dropwise over 2 h. The reaction was monitored by TLC. Upon consumption of the starting material, distilled H2O (50 mL) was added and the aqueous solution was extracted with Et2O (3 × 30 mL). The combined organic phases were dried (MgSO4), filtered, and evaporated, and the crude product was purified by flash column chromatography (hexane–EtOAc, 2:1) to give 2 as a colorless oil; yield: 1.28 g (75%); $R_f = 0.58$ (hexane–EtOAc 2:1).

IR (neat): 2972, 2940, 1751 cm⁻¹.

**1H NMR (500 MHz, CDCl3):** δ = 3.72 (s, 3H, OCH3), 2.34 (s, 2H, CH2), 1.29 (s, 6H, 2 × CH3), 1.26 (s, 6H, 2 × CH3).

**13C NMR (125 MHz, CDCl3):** δ = 216.3 (C=O), 67.2 (C), 65.2 (CH2), 61.2 (OCH3), 49.76 (C), 31.59 (2 × CH3), 22.65 (2 × CH3).

**MS (EI):** $m/z$ (%) = 171 (3, [M]+), 156 (25), 70 (48), 42 (100).
2,2,5,5-Tetramethyl-1-trifluoroacetylpyrrolidin-3-one (5)
To a stirred solution of a mixture of 4 (1.2 g, 8.5 mmol) and Et₂N (1.01 g, 10.0 mmol) in DCM (20 mL) was added (CF₃CO)₂O (2.1 g, 10.0 mmol). The mixture was refluxed for 1 h. After cooling, the mixture was diluted with distilled H₂O (10 mL), and filtered. The filter cake was washed with cold Et₂O (2 × 50 mL) and the organic phase was separated. It was then dried (MgSO₄), filtered, and evaporated to give 5 as a yellow oil; yield: 1.08 g (84%). The oil solidified upon standing in a refrigerator.

IR (neat): 3087, 3045, 2976, 1668 cm⁻¹.

1H NMR (500 MHz, CDCl₃): δ = 8.17 (s, 1 H, ArH), 7.82 (d, J = 8.5 Hz, 2 H, ArH), 7.95 (t, J = 8.5 Hz, 1 H, ArH), 7.93 (t, J = 8.5 Hz, 1 H, ArH), 3.91 (s, 6 H, 2 × CH₃), 1.55 (s, 12 H, 4 × CH₃).

13C NMR (125 MHz, CDCl₃): δ = 162.3 (2 C), 141.3 (2 C), 132.9 (2 × CH), 131.6 (CH), 129.6 (CH), 66.0 (2 × CH₂), 28.0 (2 × CH₃), 24.0 (2 × CH₃).

MS (EI): m/z (%) = 436 (27, [M⁺]), 421 (2), 375 (1), 329 (1), 43 (27).

13C NMR (125 MHz, CDCl₃): δ = 160.2 (2 C), 142.9 (2 C), 129.1 (2 × CH₂), 128.9 (2 × CH), 65.8 (2 C), 65.7 (OCH₃), 27.2 (2 × CH₃), 23.2 (2 × CH₃).

MS (EI): m/z (%) = 257 (31, [M⁺]), 242 (100), 196 (38), 42 (31).


2-Methoxy-1,1,3,3-tetramethyl-2,3-dihydro-1H-pyrrolo[3,4-b]quinoloxaline (7b)
Yield: 900 mg (70%); white powder; mp 131–134 °C; Rf = 0.63 (hexane–EtOAc 2:1).

IR (neat): 3027, 3101, 1658, 1501 cm⁻¹.

1H NMR (500 MHz, CDCl₃): δ = 8.06 (s, 2 H, ArH), 8.33 (d, J = 8.5 Hz, 2 H, ArH), 7.80 (d, J = 8.5 Hz, 1 H, ArH), 7.79 (t, J = 8.5 Hz, 1 H, ArH), 3.82 (s, 3 H, OCH₃), 1.55 (s, 12 H, 4 × CH₃).

13C NMR (125 MHz, CDCl₃): δ = 160.4 (2 C), 151.2 (OCH₃), 129.6 (2 × CH), 129.7 (2 × CH), 128.8 (2 × CH), 66.0 (OCH₃), 28.0 (2 × CH₂), 24.0 (2 × CH₃).

MS (EI): m/z (%) = 323 (7, [M⁺]), 285 (100), 196 (38), 123 (100), 42 (2).
7-Methoxy-6,6,8,8-tetramethyl-7,8-dihydro-6H-pyrrolo[3,4-g]pteridine (12b)

To a solution of compound 3 (555 mg, 3.0 mmol) in glacial AcOH (10 mL) was added compound 12a (330 mg, 3.0 mmol) and the mixture was refluxed for 3 h. After cooling, the solvent was evaporated, and the residue was treated with distilled H2O (20 mL) and sat. aq K2CO3 (20 mL). The mixture was extracted with CHCl3 (3 × 30 mL), the combined organic phases were dried (MgSO4), filtered, and evaporated. The residue was purified by flash column chromatography (hexane–EtOAc, 1:1) to give compound 12b as a beige powder; yield: 385 mg (50%); mp 115–117 °C; Rf = 0.57 (CHCl3–Et2O 2:1).

To a suspension of compound 12b (25 mL) was added powdered NaHCO3 (336 mg, 4.0 mmol) and the mixture was stirred at r.t. for 15 min. Then a solution of compound 370 mg, 2.0 mmol) in MeOH (20 mL) was added to the mixture. The resulting mixture was refluxed for 3 h. After cooling, the mixture was filtered on a sintered glass funnel to remove inorganic salts. The solvents were evaporated, and the residue was partitioned between distilled H2O (15 mL), MeOH (5 mL), and CHCl3 (20 mL). The organic phase was separated, dried (MgSO4), filtered and evaporated. The residue was purified by flash column chromatography (hexane–EtOAc, 1:1) to give compound 13b as an orange powder; yield: 350 mg (60%); mp 166–168 °C; Rf = 0.14 (CHCl3–MeOH 2:1).

The residue was treated with distilled H2O (20 mL) and sat. aq K2CO3 (20 mL). The mixture was extracted with CHCl3 (3 × 30 mL), the combined organic phases were dried (MgSO4), filtered, and evaporated. The residue was purified by flash column chromatography (hexane–EtOAc, 1:1) to give compound 13b as a beige powder; yield: 385 mg (50%); mp 115–117 °C; Rf = 0.57 (CHCl3–Et2O 2:1).

IR (neat): 3068, 1616, 1573 cm–1.

1H NMR (500 MHz, CDCl3): δ = 9.67 (s, 1 H, ArH), 9.51 (s, 1 H, ArH), 3.86 (s, 3 H, OCH3), 1.63 (s, 12 H, 4 × CH3).

13C NMR (125 MHz, CDCl3): δ = 169.2 (CH), 163.9 (CH), 162.4 (C), 158.0 (C), 154.6 (C), 134.6 (C), 66.4 (C), 66.0 (C), 65.8 (OCH3), 28.13 (2 × CH3), 23.02 (2 × CH3).


Preparation of 7c, 10c, 11c, 12c, 13c, 17, 23, and 27 by Deproteinization of Methoxamines; General Procedure

Methoxyamine 7b or 10b or 11b or 12b or 13b or 16b or 22b or 26b (2.0 mmol) was stirred in DCM (20 mL) at r.t. Solid 3-chloroperbenzoic acid (–60%, 172 mg, 0.6 mmol) was added in 2–3 portions at 0 °C over 10 min. The solution turned yellow-orange, and the stirring was continued for an additional 30 min at r.t. Then, the solution was washed with 10% aq Na2CO3 (2 × 10 mL), and the organic phase was separated, dried (MgSO4), filtered, and evaporated. The residue was subjected to flash column chromatography (hexane–EtOAc, 2:1) to afford compound 7c as a yellow powder; yield: 58 mg (48%); mp 168–170 °C; Rf = 0.41 (hexane–EtOAc, 2:1).
(1,1,3,3-Tetramethyl-2,3-dihydro-1H-pyrrolo[3,4-b]quinoxaline-5-carboxamide-2-yl)oxidanyl (10c)

Purified by flash column chromatography (hexane–EtOAc 2:1) to obtain an orange powder; yield: 348 mg (61%); mp 249–252 °C; Rf = 0.30 (CHCl₃–EtO₂; 2:1).

IR (neat): 3509, 3181, 3044, 2979, 1730, 1702, 1673, 1537 cm⁻¹.

1H NMR (500 MHz, DMSO-d₆): δ = 8.49 (s, 1 H, NH), 7.46 (d, J = 7.5 Hz, 2 H, ArH), 5.82 (dd, J = 7.5 Hz, 1 H, ArH), 4.26 (m, 2 H, ArH and NH₂). 8.08 (8 H, ArH). 1.37 (s, 12 H, 4 × CH₃).

13C NMR (125 MHz, DMSO-d₆): δ = 164.2 (C=O), 151.7 (CH), 145.0 (CH), 134.8 (C), 130.7 (CH), 129.0 (2 × CH), 128.5 (2 × CH), 128.4 (C), 123.3 (C), 25.4 (2 × CH₃), 25.2 (2 × CH₃).

MS (EI): m/z (%) = 406 (100, [M⁺]), 391 (63), 361 (48), 346 (43), 331 (38).

Anal. Calcd for C₁₁H₁₅N₄O₂: C, 56.16; H, 6.43; N, 23.81. Found: C, 56.04; H, 6.35; N, 23.81.

(5,5,7,7-Tetramethyl-5H-pyrrolo[3,4-b]pyrazin-6-yl)oxidanyl (17)

Purified by flash column chromatography (CHCl₃–Et₂O 2:1) to afford a yellow powder; yield: 100 mg (65%); mp 202–205 °C; Rf = 0.43 (hexane–EtOAc 2:1).

IR (neat): 3357, 3180, 2984, 1672, 1575 cm⁻¹.

1H NMR (500 MHz, DMSO-d₆): δ = 8.47 (s, 2 H, ArH), 1.36 (s, 12 H, 4 × CH₃).

13C NMR (125 MHz, DMSO-d₆): δ = 159.0 (2 C), 144.2 (2 × CH), 65.3 (2 C), 25.3 (2 × CH₃), 25.1 (2 × CH₃).

MS (EI): m/z (%) = 244 (77, [M⁺]), 214 (28), 213 (33), 199 (100), 184 (76).


(6,6,8,8-Tetramethyl-6H-pyrrolo[3,4-g]pteridin-7-yl)oxidanyl (12c)

Purified by flash column chromatography (hexane–EtOAc 2:1) to afford a brown powder; yield: 328 mg (52%); mp 235–238 °C; Rf = 0.44 (CHCl₃–EtO₂; 2:1).

IR (neat): 3063, 3023, 2979, 2931, 1615, 1572, 1556 cm⁻¹.

1H NMR (500 MHz, CDCl₃ + (PhNH)₂): δ = 8.74 (s, 1 H, ArH), 9.61 (s, 1 H, ArH), 7.91 (s, 1 H, ArH), 1.71 (s, 6 H, 2 × CH₃), 1.67 (s, 6 H, 2 × CH₃).

13C NMR (125 MHz, CDCl₃ + (PhNH)₂): δ = 169.2 (CH), 163.4 (C=O), 161.4 (CH), 159.2 (C), 149.2 (CH), 132.2 (CH), 128.5 (2 × CH₃), 25.0 (2 × CH₃), 24.8 (2 × CH₃).

MS (EI): m/z (%) = 837 (100, [M⁺]), 276 (76), 254 (40), 77 (15).

Anal. Calcd for C₁₂H₁₄N₅O: C, 56.14; H, 6.43; N, 23.76. Found: C, 56.04; H, 6.45; N, 23.76.

(1,4,4,6,6-Pentamethyl-2-phenyl-4,6-dihydropyrrolo[3,4-b]pyrazine-2-carboxamide-6-yl)oxidanyl (23)

Purified by flash column chromatography (CHCl₃–Et₂O 2:1) to afford yellow crystals; yield: 350 mg (65%); mp 133–135 °C; Rf = 0.47 (CHCl₃–EtO₂; 2:1).

IR (neat): 3330, 3181, 2984, 1672, 1575 cm⁻¹.

1H NMR (500 MHz, DMSO-d₆ + (PhNH)₂): δ = 7.69 (d, J = 7.5 Hz, 2 H, ArH), 7.47–7.44 (m, 1 H, ArH), 6.94 (2 aromatic H overlapped with (PhNH)₂ signals), 3.69 (s, 3 H, NCH₃), 1.39 (s, 6 H, 2 × CH₃), 1.38 (s, 6 H, 2 × CH₃).

13C NMR (125 MHz, CDCl₃ + (PhNH)₂): δ = 150.2 (C), 148.9 (C), 145.8 (C), 134.8 (C), 130.7 (CH), 129.0 (2 × CH), 128.5 (2 × CH), 64.7 (C), 64.1 (C), 32.4 (NCH₃), 25.4 (2 × CH₃), 25.2 (2 × CH₃).

MS (EI): m/z (%) = 270 (2, [M⁺]), 240 (100), 225 (89), 211 (20), 77 (15), 43 (16).

1H NMR [500 MHz, CDCl3 + (PhNH)2]: δ = 3.73 (s, 3 H, OCH3), 3.54 (s, 4 H, 2 × CH2), 1.34 (s, 12 H, 4 × CH3).

13C NMR [125 MHz, CDCl3 + (PhNH)2]: δ = 166.1 (2 C), 65.6 (OCH3), 64.3 (2 C), 44.9 (2 × CH2), 27.0 (2 × CH3), 21.0 (2 × CH2).

MS (EI): m/z (%) = 209 (31, [M]+), 194 (100), 162 (62), 42 (34).


To a stirred solution of compound 15 (418 mg, 2.0 mmol) in anhyd MeOH (10 mL) was added a solution of NaOMe [freshly prepared from Na (92 mg, 4.0 mmol) and anhyd EtOH (20 mL)] and then, the resulting mixture was refluxed for 4 h under N2. After cooling, the solvents were evaporated, and the residue was partitioned between sat. aq NH4Cl (20 mL) and CH2Cl2 (50 mL). The organic phase was separated, dried (MgSO4), filtered, and evaporated. The residue was purified by flash column chromatography (hexane–EtOAc 2:1) to give compound 16 as a colorless oil; yield: 223 mg (54%); Rf = 0.56 (hexane–EtOAc 2:1).

IR (neat): 3086, 2979, 2968, 1691, 1588 cm–1.


1H NMR [500 MHz, CDCl3 + (PhNH)2]: δ = 8.38 (s, 2 H, ArH), 8.33 (s, 3 H, OCH3), 1.51 (s, 12 H, 4 × CH3).

13C NMR [125 MHz, CDCl3 + (PhNH)2]: δ = 158.8 (2 C), 143.7 (2 × CH), 65.8 (OCH3), 65.6 (2 C), 28.2 (2 × CH3), 23.5 (2 × CH2).

MS (EI): m/z (%) = 207 (15, [M]+), 192 (100), 163 (24), 42 (42).


(1-Oxyl-5,5,7,7-tetramethyl-5,6-dihydro-5H-pyrrolo[3,4-b]pyrazin-6-yl)oxidi- danyl (18)

To a stirred solution of compound 17 (768 mg, 4.0 mmol) in DCM (40 mL) was added solid 3-chloroperbenzoic acid (~60%, 5.73 g, 20.0 mmol) over a period of 1 h. The reaction was monitored by TLC, and upon the consumption of the starting material (24 h), the precipitated 3-chloroanisole was filtered out on a sintered glass funnel. DCM (40 mL) was added and the organic phase was washed with aq 5% H2SO4 (pH 2). The aqueous phase was extracted with CHCl3 (2 × 30 mL). The combined organic phases were dried (MgSO4), filtered, and evaporated. The residue was purified by flash column chromatography (hexane–EtOAc 2:1) to give compound 18 as a colorless oil; yield: 502 mg (36%); Rf = 0.33 (hexane–EtOAc 2:1).

IR (neat): 2979, 2936, 1720, 1573, 1559 cm–1.

1H NMR [500 MHz, CDCl3]: δ = 9.09 (s, 1 H, ArH), 4.52 (q, J = 7.5 Hz, 2 H, OCH2CH3), 3.81 (s, 3 H, OCH3), 1.55 (s, 12 H, 4 × CH3), 1.46 (t, J = 7.5 Hz, 3 H, OCH2CH3).

13C NMR [125 MHz, CDCl3]: δ = 164.4 (C=O), 162.3 (C), 158.9 (C), 145.4 (CH), 143.0 (60.0 (2 × CH3), 65.7 (OCH3), 62.0 (2 × CH2), 28.9 (2 × CH3), 14.3 (CH3).

MS (EI): m/z (%) = 279 (12, [M]+), 264 (100), 218 (6).

purified by flash column chromatography (hexane–EtOAc, 2:1) to give compound 22 as a beige solid; yield: 247 mg (66%); mp 158–160 °C; Rf = 0.36 (CHCl3–EtOAc 2:1).

IR (neat): 3440, 3197, 2977, 2948, 1685, 1575 cm⁻¹.

1H NMR (500 MHz, DMSO-d₆): δ = 9.03 (s, 1 H, NH), 8.18 (s, 1 H, NH₂), 7.84 (s, 1 H, ArH), 3.77 (s, 3 H, OCH₃), 1.45 (s, 12 H, 4 × CH₃).

13C NMR (125 MHz, CDCl₃): δ = 165.4 (C=O), 160.9 (C), 156.8 (C), 145.3 (CH), 143.4 (C₆H₅), 66.1 (C), 65.8 (C), 65.7 (OCH₃), 27.7 (2 × CH₃), 23.3 (2 × CH₃).

MS (EI): m/z (%) = 285 (32, [M]+), 270 (54), 238 (100), 43 (28).


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**Supporting Information**

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**References**


