2-(Nitroaryl)benzothiazole and benzoxazole derivatives as fluorogenic substrates for the detection of nitroreductase activity in microorganisms

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Supplementary information

Synthetic work

$^1$H-NMR spectra (400 MHz) and $^{13}$C-NMR spectra (101 MHz) were recorded on a Jeol ECS400 instrument. High resolution mass spectrometry (HRMS) was performed by the EPSRC mass spectrometry service. Infrared spectra were obtained via a diamond anvil sample cell using a Perkin Elmer 1000 spectrometer. Melting points are reported uncorrected as determined on a Stuart SMP 1 melting point apparatus. Thin layer chromatography was performed on Merck plastic foil plates pre-coated with silica gel 60 F$_{254}$. Merck silica gel 60 was used for column chromatography. Compound 6a was prepared following a literature procedure (ref. 13 in text). The synthesis of compounds 3c and 4c have previously been described by us (ref. 11 in text).

General method for the synthesis of substrates 7a-d.

A mixture of 3-amino-4-hydroxybenzoic acid or 4-amino-3-hydroxybenzoic acid (1.0 equiv) and an appropriate 2-nitrobenzaldehyde derivative (1.0 equiv) was heated in EtOH at reflux for 1 h. The reaction mixture was allowed to cool to room temperature and the resulting precipitate (compound 12) was collected, washed with water, dried under vacuum overnight and used directly in the next step. The precipitate and DDQ (1.0 equiv) in anhydrous 1,4-dioxane was stirred at room temperature. The reaction mixture was then filtered and the filtrate was evaporated giving the substrate 7.

2-(2-Nitrophenyl)benzoxazole-6-carboxylic acid (7a).

4-Amino-3-hydroxybenzoic acid (0.30 g, 1.96 mmol) and 2-nitrobenzaldehyde (0.30 g, 1.96 mmol) in ethanol (30 mL) at reflux for 16 hours gave compound 12a which was reacted with DDQ (0.44 g, 1.96 mmol) in 1,4-dioxane (50 mL) for 16 h. Compound 7a was obtained as a brown solid (0.53 g, 1.86 mmol, 95%), m.p. 252-254 °C; HRMS found M+H: 285.0510. Calcd. for C$_{14}$H$_9$N$_2$O$_5$; M+H: 285.0506; IR $\nu_{\text{max}}$ (cm$^{-1}$): 3000 (OH), 1688 (C=O), 1530, 1417, 1294, 1276; $^1$H-NMR (400 MHz, d$_6$-DMSO) $\delta$H 8.32 (1H, d, $J = 1.6$ Hz, C7-H), 8.25 (1H, m, Ar-H), 8.18 (1H, m, Ar-H), 8.07 (1H, dd, $J = 8.2$ and 1.6 Hz, C5-H), 7.96 (3H, m, 3 x Ar-H); $^{13}$C-NMR (101 MHz, d$_6$-DMSO) $\delta$C 167.2 (C=O), 161.1 (C), 150.6 (C), 149.2 (C), 145.0 (C), 134.0 (CH), 133.9 (CH), 132.0 (CH), 129.4 (C), 127.0 (CH), 125.1 (CH), 120.7 (CH), 120.0 (C), 112.9 (CH).
2-(2-Nitrophenyl)benzoxazole-5-carboxylic acid (7b).

3-Amino-4-hydroxybenzoic acid (1.00 g, 6.53 mmol) and 2-nitrobenzaldehyde (1.09 g, 7.18 mmol) in ethanol (50 mL) at reflux for 16 hours gave compound 12b which was reacted with DDQ (0.95 g, 4.19 mmol) in 1,4-dioxane (50 mL) for 62 h. Compound 7b was obtained as a brown solid (0.53 g, 1.86 mmol, 53%), m.p. 240-243 °C; HRMS found M+H: 285.0509. Calcd. for C_{14}H_{9}N_{2}O_{5}^+, M+H: 285.0506; IR ν_{max} (cm^{-1}) 3108 (OH), 1672 (C=O), 1534, 1554, 1268, 1172; 1H-NMR (400 MHz, d_{6}-DMSO) δ_{H} 8.37 (1H, broad s, C4-H), 8.24 (1H, d, J = 7.3 Hz, Ar-H), 8.18 (1H, d, J = 7.3 Hz, Ar-H), 8.11 (1H, d, J = 8.7 Hz, Ar-H), 7.95 (3H, m, 3 x Ar-H); 13C-NMR (101 MHz, d_{6}-DMSO) δ_{C} 167.3 (C=O), 160.3 (C), 153.5 (C), 149.1 (C), 141.6 (C), 133.9 (2 x 2CH), 132.0 (CH), 128.8 (C), 128.3 (CH), 125.2 (CH), 122.1 (CH), 120.1 (C), 111.9 (CH).

2-(5-Fluoro-2-nitrophenyl)benzoxazole-6-carboxylic acid (7c).

4-Amino-3-hydroxybenzoic acid (0.20 g, 1.31 mmol) and 5-fluoro-2-nitrobenzaldehyde (0.22 g, 1.31 mmol) in ethanol (30 mL) at reflux for 16 hours gave compound 12c which was reacted with DDQ (0.30 g, 1.31 mmol) in 1,4-dioxane (50 mL) for 16 hours. Compound 7c was obtained as a brown solid (0.04 g, 0.15 mmol, 11%), m.p. 236-238 °C after purification by column chromatography over silica gel (eluent: ethyl acetate); HRMS found M+H: 303.0407. Calcd. for C_{14}H_{8}FN_{2}O_{5}^+, M+H: 303.0412; IR ν_{max} (cm^{-1}): 3000 (OH), 1679 (C=O), 1541, 1496, 1268, 1216; 1H-NMR (400 MHz, d_{6}-DMSO) δ_{H} 8.31 (2H, m, 2 x Ar-H), 8.11 (1H, dd, J = 8.2 Hz and 2.8 Hz, Ar-H), 8.07 (1H, dd, J = 8.2 Hz and 1.4 Hz, Ar-H), 7.98 (1H, dd, J = 8.2 Hz, Ar-H), 7.83 (1H, m, Ar-H); 13C-NMR (101 MHz, d_{6}-DMSO) δ_{C} 167.1 (C=O), 165.1 (d, J = 254.0 Hz, CF), 160.3 (C), 150.6 (C), 145.6 (C), 144.8 (C), 129.7 (C), 128.5 (d, J = 9.6 Hz, CH), 127.1 (CH), 123.2 (d, J = 10.5 Hz, C), 120.9 (CH), 120.7 (CH), 119.4 (d, J = 26.8 Hz, CH), 112.9 (CH).

2-(5-Fluoro-2-nitrophenyl)benzoxazole-5-carboxylic acid (7d).

Compound 7d (95%) was prepared in a similar manner to compound 7c and was obtained as a yellow solid m.p. 217-220 °C. HRMS found M+H: 303.0416. Calcd. for C_{14}H_{8}FN_{2}O_{5}^+, M+H: 303.0412; IR ν_{max} (cm^{-1}): 1683 (C=O), 1537, 1292; 1H-NMR (400 MHz, d_{6}-DMSO) δ_{H} 8.32 (1H, d, J = 1.6 Hz, C4-H), 8.26 (1H, dd, J = 8.7 and 4.6 Hz, Ar-H), 8.07 (1H, dd, J = 8.7 and 1.6 Hz, C6-H), 8.04 (1H, dd, J = 8.7 and 2.9 Hz, Ar-H), 7.89 (1H, dd, J = 8.7 Hz, C7-H), 7.76 (1H, dd, J = 7.8 and 2.9 Hz, Ar-H); 13C-NMR (101 MHz, d_{6}-DMSO) δ_{C} 167.2 (C=O), 163.8 (d, J = 254.0 Hz, CF), 159.2 (C), 153.5 (C), 145.5 (d, J = 2.9 Hz, C), 141.4 (C), 128.9 (C), 128.5 (CH), 128.4 (CH), 123.1 (d, J = 10.5 Hz, C), 122.2 (CH), 120.7 (d, J = 23.0 Hz, CH), 119.3 (d, J = 26.8 Hz, CH), 112.0 (CH).

Potassium salt of carboxylic acid 7a.

Potassium 2-(2-nitrophenyl)benzoxazole-6-carboxylate
To compound 7a (98 mg, 0.35 mmol) was added a solution of methanolic KOH solution (34 mM, 10.3 mL, 0.35 mmol) at room temperature with stirring. The solvent was evaporated to yield the potassium salt (106 mg, 94%) as a dark brown solid; δ\textsubscript{H} (400 MHz, D\textsubscript{2}O) 7.61-7.57 (2H, m, 2 x Ar-H), 7.55-7.48 (2H, m, 2 x Ar-H), 7.37 (2H, m, 2 x Ar-H), 7.28 (1H, dd, J = 8.2 and 1.8 Hz, C7-H).

**General procedure for the preparation of the benzothiazole derivatives 9a-9c.**

Compound 3c (1 equiv), an appropriate amine (1.1 equiv) and NaHCO\textsubscript{3} (2.5 equiv) were added to THF and H\textsubscript{2}O (50 mL, 1:1) and the mixture was heated under reflux for 16 h. The reaction was allowed to cool and the THF was evaporated. The remaining solution was then acidified to pH 1-2 with 2M aqueous HCl. The resulting precipitate was collected giving the desired compound.

**(2R)-1-[3-(1,3-Benzothiazol-2-yl)-4-nitrophenyl]pyrrolidine-2-carboxylic acid (9a).**

Compound 9a was prepared from compound 3c (0.10 g, 0.37 mmol), L-proline (0.05 g, 0.40 mmol) and NaHCO\textsubscript{3} (0.08 g, 0.91 mmol). Compound 9a was obtained as a yellow solid (0.13 g, 0.35 mmol, 95%), m.p. decomposes from 132 °C. HRMS found M+H: 370.0857. Calcd. for C\textsubscript{18}H\textsubscript{16}N\textsubscript{3}O\textsubscript{4}S\textsuperscript{+}, M+H: 370.0856; IR ν\textsubscript{max} (cm\textsuperscript{-1}): 3000 (OH), 1728 (C=O), 1594, 1504, 1309; 1H-NMR (400 MHz, d\textsubscript{6}-DMSO) δ\textsubscript{H} 8.15 (1H, d, J = 7.3 Hz, Ar-H), 8.07 (1H, d, J = 9.2 Hz, Ar-H), 8.01 (1H, d, J = 7.8 Hz, Ar-H), 7.54 (1H, td, J = 6.9 and 1.4 Hz, Ar-H), 7.48 (1H, td, J = 6.9 and 1.4 Hz, Ar-H), 6.67 (2H, broad s, 2 x Ar-H), 4.49 (1H, dd, J = 8.7 and 2.3 Hz, N-CH\textsubscript{2}), 3.54 (1H, m, N-C\textsubscript{H}), 3.43 (1H, m, N-C\textsubscript{H}), 2.26 (1H, m, CH\textsubscript{2}), 2.11 (1H, m, CH\textsubscript{2}), 1.97 (2H, m, 2 x CH\textsubscript{2}); 13C-NMR (101 MHz, d\textsubscript{6}-DMSO) δ\textsubscript{C} 173.9 (C=O), 165.2 (C\textsubscript{2}), 153.3 (C\textsubscript{3}), 150.5 (C\textsubscript{4}), 136.2 (C\textsubscript{5}), 136.0 (C\textsubscript{6}), 131.5 (C\textsubscript{7}), 128.3 (C\textsubscript{8}), 127.1 (C\textsubscript{9}), 126.2 (C\textsubscript{10}), 123.6 (C\textsubscript{11}), 122.8 (C\textsubscript{12}), 114.6 (C\textsubscript{13}), 113.1 (C\textsubscript{14}), 60.9 (N-C\textsubscript{H}), 49.0 (N-C\textsubscript{2}), 30.7 (C\textsubscript{2}), 23.9 (CH\textsubscript{2}).

**(2S)-1-[3-(1,3-Benzothiazol-2-yl)-4-nitrophenyl]pyrrolidine-2-carboxylic acid (9b).**

Compound 9b was prepared from compound 3c (0.10 g, 0.37 mmol), D-proline (0.05 g, 0.40 mmol) and NaHCO\textsubscript{3} (0.08 g, 0.91 mmol). Compound 9b was obtained as a yellow solid (0.11 g, 0.30 mmol, 80%), m.p. decomposes from 132 °C. HRMS found M+H: 370.0850. Calcd. for C\textsubscript{18}H\textsubscript{16}N\textsubscript{3}O\textsubscript{4}S\textsuperscript{+}, M+H: 370.0856; IR ν\textsubscript{max} (cm\textsuperscript{-1}): 3338 (OH), 1730 (C=O), 1596, 1500, 1309; 1H-NMR (400 MHz, d\textsubscript{6}-DMSO) δ\textsubscript{H} 8.19 (1H, d, J = 7.3 Hz, Ar-H), 8.11 (1H, d, J = 9.6 Hz, Ar-H), 8.05 (1H, d, J = 7.8 Hz, Ar-H), 7.58 (1H, td, J = 7.8 Hz and 1.4 Hz, Ar-H), 6.71 (2H, broad s, 2 x Ar-H), 4.53 (1H, dd, J = 8.7 and 2.3 Hz, N-CH\textsubscript{2}), 3.50 (2H, m, 2 x N-CH\textsubscript{2}), 2.30 (1H, m, CH\textsubscript{2}), 2.15 (1H, m, CH\textsubscript{2}), 2.00 (2H, m, 2 x CH\textsubscript{2}); 13C-NMR (101 MHz, d\textsubscript{6}-DMSO) δ\textsubscript{C} 173.9 (C=O), 165.2 (C\textsubscript{2}), 153.3 (C\textsubscript{3}), 150.5 (C\textsubscript{4}), 136.2 (C\textsubscript{5}), 136.0 (C\textsubscript{6}), 131.5 (C\textsubscript{7}), 128.3 (C\textsubscript{8}), 127.1 (C\textsubscript{9}), 126.2 (C\textsubscript{10}), 123.6 (C\textsubscript{11}), 122.8 (C\textsubscript{12}), 114.6 (C\textsubscript{13}), 113.1 (C\textsubscript{14}), 60.9 (N-C\textsubscript{H}), 49.0 (N-C\textsubscript{2}), 30.7 (C\textsubscript{2}), 23.9 (CH\textsubscript{2}).

(2R)-1-[3-(1,3- Benzothiazol-2-yl)-4-nitrophenyl]pyrrolidine-2-carboxylic acid (9a).

(2S)-1-[3-(1,3- Benzothiazol-2-yl)-4-nitrophenyl]pyrrolidine-2-carboxylic acid (9b).
4-\{3-(1,3- Benzothiazol-2-yl)-4-nitrophenyl\}(methyl)amino\}butanoic acid (9e).

Compound 9c was prepared from compound 3c (0.10 g, 0.37 mmol), N-methylaminobutyric acid hydrochloride (0.05 g, 0.40 mmol) and NaHCO₃ (0.08 g, 0.91 mmol). Compound 9c was obtained as a yellow solid (0.11 g, 0.29 mmol, 79%), m.p. 163-166 °C. HRMS found M+H: 372.1014. Calcd for C₁₈H₁₈N₃O₄S+, M+H: 372.1013; IR νₘₐₓ (cm⁻¹): 2919 (OH), 1718 (C=O), 1597, 1493, 1302; ¹H-NMR (400 MHz, d₆-DMSO) δH 8.19 (1H, d, J = 7.7 Hz, Ar-H), 8.09 (1H, d, J = 9.2 Hz, Ar-H), 8.06 (1H, d, J = 7.7 Hz, Ar-H), 7.58 (1H, td, J = 7.7 and 1.4 Hz, Ar-H), 7.52 (1H, td, J = 7.7 and 1.4 Hz, Ar-H), 6.97 (1H, dd, J = 9.2 and 2.8 Hz, C₂′-H), 6.92 (1H, d, J = 2.8 Hz, C₂′-H), 3.51 (2H, t, J = 7.3 Hz, N-CH₂), 3.09 (3H, s, N-CH₃), 2.29 (2H, t, J = 7.3 Hz, C₄H₂-CO₂H), 1.77 (2H, quintet, J = 7.3 Hz, C₄H₂). ¹³C-NMR (101 MHz, d₆-DMSO) δC 174.7 (C=O), 165.6 (C), 153.3 (C), 152.5 (C), 136.1 (C), 135.4 (C), 131.8 (C), 128.4 (CH), 127.0 (CH), 126.1 (CH), 123.6 (CH), 122.8 (CH), 113.8 (CH), 112.2 (CH), 51.5 (N-CH₂), 38.9 (N-CH₃), 31.0 (C₄H₂), 22.0 (CH₂).

General procedure for the preparation of the benzoxazole derivatives 10a-c.

Compound 4c (1 equiv), an appropriate amine (1.1 equiv) and NaHCO₃ (2.5 equiv) were added to EtOH and H₂O (50 mL, 1:1) and the mixture was heated under reflux for 16 h. The reaction was allowed to cool and the EtOH was evaporated. The remaining solution was then acidified to pH 1-2 with 2M aqueous HCl. EtOAc was then added and the organic layer was separated. The organic layer was washed successively with H₂O and then brine, dried (MgSO₄) and evaporated yielding the product.

(2R)-1-[3-(1,3-Benzoxazol-2-yl)-4-nitrophenyl]pyrrolidine-2-carboxylic acid (10a).

Compound 10a was prepared from compound 4c (0.50 g, 1.93 mmol), L-proline (0.25 g, 2.13 mmol) and NaHCO₃ (0.41 g, 4.83 mmol). Compound 10a was obtained as a yellow solid (0.49 g, 1.38 mmol, 71%), 207-209 °C. HRMS found M+H: 354.1084. Calcd. for C₁₈H₁₆N₃O₅+, M+H: 354.1084; IR νₘₐₓ (cm⁻¹): 2858 (OH), 1728 (C=O), 1586, 1287; ¹H-NMR (400 MHz, d₆-DMSO) δH 8.17 (1H, d, J = 9.2 Hz, Ar-H), 7.86 (1H, m, Ar-H), 7.78 (1H, m, Ar-H), 7.47 (2H, m, 2 x Ar-H), 6.93 (1H, broad s, Ar-H), 6.81 (1H, broad s, Ar-H), 4.55 (1H, dd, J = 8.2 Hz and 1.8 Hz, N-CH₃), 3.59 (1H, m, N-CH₃), 3.49 (1H, m, N-CH₃), 2.31 (1H, CH), 2.17 (1H, m, CH₂), 2.02 (2H, m, 2 x CH₂), 1.3-C-NMR (101 MHz, d₆-DMSO) δC 173.7 (C=O), 161.2 (C), 151.0 (C), 150.8 (C), 141.5 (C), 136.0 (C), 128.3 (CH), 126.3 (CH), 125.6 (C), 125.4 (CH), 120.6 (CH), 115.0 (CH), 113.8 (CH), 111.6 (CH), 60.9 (N-CH₂), 49.1 (N-CH₂), 30.7 (CH₂), 23.8 (CH₂).

(2S)-1-[3-(1,3-Benzoxazol-2-yl)-4-nitrophenyl]pyrrolidine-2-carboxylic acid (10b).

Compound 10b was prepared from compound 4c (0.50 g, 1.93 mmol), D-proline (0.25 g, 2.13 mmol) and NaHCO₃ (0.41 g, 4.83 mmol). Compound 10b was obtained as a yellow solid (0.59 g, 1.68 mmol, 87%), m.p. 207-209 °C. HRMS found M+H: 354.1082. Calcd. for
C₁₈H₁₆N₃O₅⁺, M+H: 354.1084; IR ν max (cm⁻¹): 1727 (C=O), 1586, 1287; ¹H-NMR (400 MHz, d₆-DMSO) δH 8.18 (1H, d, J = 9.2 Hz, Ar-H), 7.87 (2H, m, 2 x Ar-H), 7.79 (1H, m, Ar-H), 7.48 (2H, m, 2 x Ar-H), 6.94 (1H, broad s, Ar-H), 6.80 (1H, broad s, Ar-H), 4.57 (1H, dd, J = 8.7 and 1.8 Hz, N-CH), 3.60 (1H, m, N-CH), 3.50 (1H, m, N-CH), 2.32 (1H, m, C-H), 2.18 (1H, m, C-H), 2.02 (2H, m, 2 x CH); ¹³C-NMR (101 MHz, d₆-DMSO) δC 173.7 (C=O), 161.2 (C), 151.0 (C), 150.8 (C), 141.5 (C), 136.0 (C), 128.3 (CH), 126.3 (CH), 125.6 (C), 125.4 (CH), 120.6 (CH), 115.0 (CH), 113.8 (CH), 111.6 (CH), 60.9 (N-CH), 49.1 (N-CH₂), 30.7 (CH₂), 23.8 (CH₂).

4-[[3-(1,3-Benzoxazol-2-yl)-4-nitrophenyl](methyl)amino]butanoic acid (10c).

Compound 10c was prepared from compound 4c (0.50 g, 1.93 mmol), N-methylaminobutyric acid hydrochloride (0.33 g, 2.13 mmol) and NaHCO₃ (0.41 g, 4.83 mmol). Compound 10c was obtained as a yellow solid (0.58 g, 1.64 mmol, 85%), m.p. 168-170 °C. HRMS found M+H: 356.1240. Calcd. for C₁₈H₁₈N₃O₅⁺, M+H: 356.1241; IR ν max (cm⁻¹): 2940 (OH), 1727 (C=O), 1587, 1308; ¹H-NMR (400 MHz, d₆-DMSO) δH 8.14 (1H, d, J = 9.2 Hz, Ar-H), 7.85 (1H, m, Ar-H), 7.78 (1H, m, Ar-H), 7.46 (2H, m, Ar-H), 7.12 (1H, d, J = 2.8 Hz, C₂'-H), 7.02 (1H, dd, J = 9.6 and 2.8 Hz, Ar-H), 3.53 (2H, t, J = 7.3 Hz, NCH₂), 3.10 (3H, s, CH₃), 2.30 (2H, t, J = 7.3 Hz, CH₂-CO₂H), 1.78 (2H, quintet, J = 7.3 Hz, CH₂); ¹³C-NMR (101 MHz, d₆-DMSO) δC 174.7 (C=O), 161.5 (C), 152.9 (C), 151.0 (C), 141.5 (C), 136.0 (C), 128.3 (CH), 126.2 (CH), 126.0 (CH), 125.3 (CH), 120.6 (CH), 114.2 (CH), 112.9 (CH), 111.6 (CH), 51.5 (N-CH), 39.0 (N-CH₂), 31.0 (CH₂), 22.1 (CH₂).

Microbiological work

Agar plate preparation

Each substrate (10 mg) was dissolved in a minimal volume of 1-methyl-2-pyrrolidone (200-400 µL) and added to molten Columbia agar (100 mL) (Oxoid, Basingstoke) at 50 ºC to a final concentration of 100 mg L⁻¹. Agar plates were then prepared and dried to remove excess moisture. Bacterial strains and yeasts obtained from various national culture collections (see Tables) were sub-cultured onto Columbia agar. Colonies of each strain were sampled using a loop and suspended in 0.85 % sterile saline to generate a suspension equivalent to 10⁸ colony forming units (cfu) per mL using a densitometer. Each agar plate was then inoculated with 1 µL of this suspension using a multipoint inoculator that delivered suspensions of 20 strains per plate. Plates were incubated at 37 °C in air for 24 h. Control plates without the substrate were prepared and inoculated concomitantly.

Fluorescence response at varying concentrations

Compound 7a (10 mg) was dissolved in 0.95 mL sterile deionised water and 50 µL of 1M sodium hydroxide solution was added to produce a solution of 10000 mg/L. The following volumes were added to brain heart infusion broth (Oxoid) to give a final volume of 20 mL: 200 µL, 100 µL, 50 µL, 25 µL and 12.5 µL. The final concentration range was 0.33 – 0.02
mmol/L. A Gram-negative isolate (Enterobacter cloacae) and a Gram-positive isolate (Staphylococcus aureus) were inoculated at a final inoculum of $10^5$ CFU/mL and the broths were incubated overnight for 18 h at 37°C. Substrate-free and bacteria-free controls were included and tests were performed in duplicate. Fluorescence was read before and after incubation on a Synergy HT microplate reader using 365 nm excitation and 440 nm emission wavelengths.