

# New *N*-phenyl-4,5-dibromopyrrolamides as DNA gyrase B inhibitors

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Electronic Supplementary Information (ESI) available: [antibacterial data; full experimental procedures; NMR spectra of the tested compounds]

## Abstract

Due to the rapid development of antimicrobial resistance, the discovery of new antibacterials is essential in the fight against potentially lethal infections. The DNA gyrase B (GyrB) subunit of bacterial DNA gyrase is an excellent target for the design of antibacterials, as it has been clinically validated by novobiocin. However, there are currently no drugs in clinical use that target GyrB. We prepared a new series of *N*-phenyl-4,5-dibromopyrrolamides and evaluated them against DNA gyrase and against the structurally and functionally similar enzyme, topoisomerase IV. The most active compound, **28**, had an IC<sub>50</sub> of 20 nM against *Escherichia coli* DNA gyrase. The IC<sub>50</sub> of **28** against *Staphylococcus aureus* DNA gyrase, and *E. coli* and *S. aureus* topoisomerase IV were in the low micromolar range. However, the compounds evaluated did not show significant antibacterial activities against selected Gram-positive and Gram-negative bacteria. Our results indicate that for potent inhibition of DNA gyrase, a combination of polar groups on the carboxylic end of the molecule and substituents that reach into the ‘lipophilic floor’ of the enzyme is required.

**Keywords:** antibacterial; DNA gyrase; GyrB; inhibitor; *N*-phenylpyrrolamide; ParE; topoisomerase IV

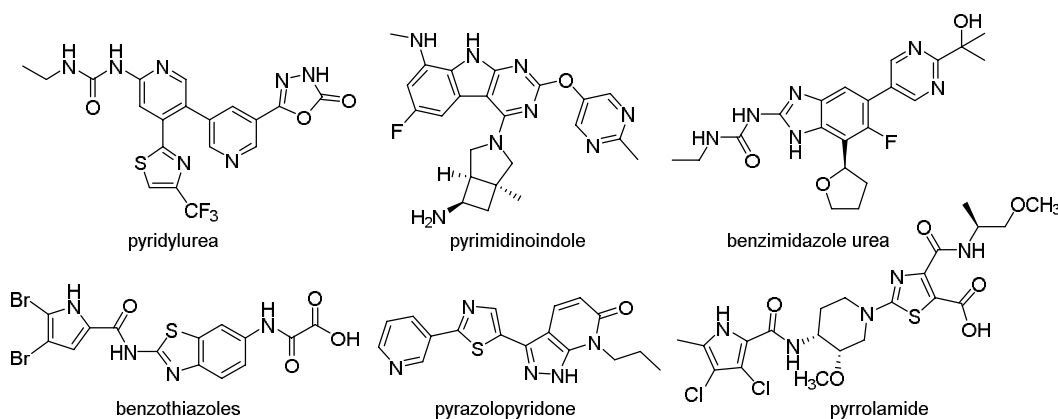
## Abbreviations

ATCC, American Type Culture Collection; GyrA, DNA gyrase A; GyrB, DNA gyrase B; RA, residual activity; TBTU, *O*-(benzotriazol-1-yl)-*N,N,N,N*-tetramethyluronium tetrafluoroborate

## 1. Introduction

Few antibacterials have reached the market over the last 50 years.<sup>1,2</sup> At the same time, the rapid spread of antibacterial resistance has become a huge problem worldwide.<sup>3</sup> Therefore, the search for new antibacterials, especially for those with new mechanisms of action or from new chemical classes, is extremely important. DNA gyrase is an enzyme that is not present in humans, but is essential for the survival of bacteria, as it is responsible for cleavage and reunion of the DNA molecule during DNA replication, transcription and recombination. In addition to DNA gyrase, bacteria have a second enzyme that is structurally and functionally similar to DNA gyrase, known as topoisomerase IV, which is also essential for bacterial cell division. Both of these enzymes are assembled as tetrameric complexes with the different subunits required for binding, cleavage and transport of DNA (DNA gyrase, 2× subunit A [GyrA]; topoisomerase IV, 2× subunit A [ParC]), and for hydrolysis of ATP (DNA gyrase, 2× subunit B [GyrB]; topoisomerase IV, 2× subunit B [ParE]).<sup>4-7</sup> The most well-known inhibitors of DNA gyrase and topoisomerase IV are the fluoroquinolones, which act by binding to the GyrA subunit and stabilising the complex between the enzyme and the DNA molecule.<sup>8</sup>

There are currently no inhibitors of GyrB in clinical use that act through an ATP-competitive mechanism. Nevertheless, several classes of ATP-competitive DNA gyrase and/or topoisomerase IV inhibitors have been discovered in recent decades,<sup>4,9,10</sup> such as pyridylureas,<sup>11</sup> pyrimidinoindoles,<sup>12</sup> benzimidazole ureas,<sup>13</sup> benzothiazoles,<sup>14-17</sup> pyrazolopyridones,<sup>18</sup> and pyrrolamides<sup>19</sup> (Fig. 1). Some of the new inhibitors have advanced to phase I clinical trials, although none of them have so far reached clinical use. Further research is required to produce drug candidates with stronger antibacterial activities and good absorption, distribution, metabolism and excretion (ADME) properties.



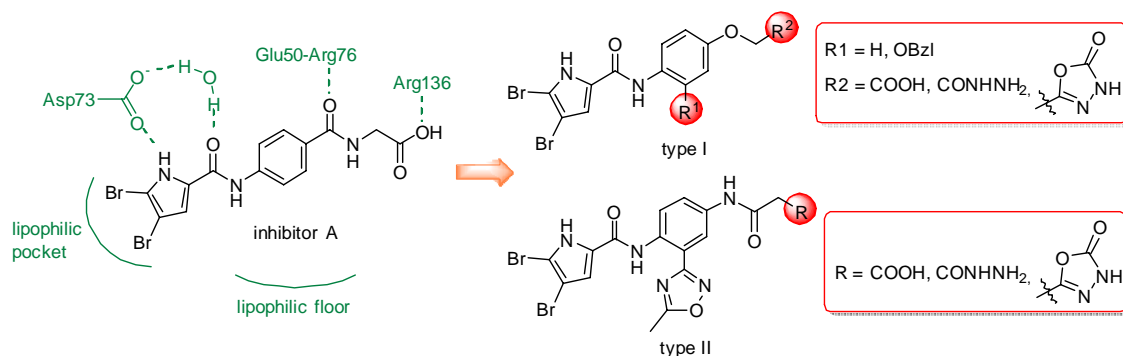
**Fig. 1** Representative ATP-competitive DNA gyrase and topoisomerase IV inhibitors.

## 2. Results and discussion

### 2.1. Design

The present series of compounds was designed using the inhibitor A-*E. coli* GyrB structure as template (PDB code: 4ZVI),<sup>20</sup> and the structure-activity relationship data derived from our previous *N*-phenylpyrrolamide GyrB inhibitors.<sup>21–24</sup> We designed two types of compounds here, types I and II, where the most important functional groups that interact with amino acid residues in the binding pocket were retained, and additional substituents were introduced to attempt to increase the binding affinities (Fig. 2). To form hydrophobic contacts in the lipophilic pocket and to make important H-bonds with Asp73, a 4,5-dibromopyrrolamide moiety was attached (Fig. 2, Inhibitor A, left side). Different groups were introduced to the central benzene ring to target either the ‘lipophilic floor’ of the enzyme (Fig. 2, type I, R<sup>1</sup>), or to establish polar interactions with the Glu50–Arg76 salt bridge or with Arg136 (Fig. 2, type I, R<sup>2</sup>; type II, R<sup>3</sup>). To investigate the importance of hydrophobic interactions with the lipophilic floor, in the type I series, derivatives with benzyloxy substituents at position R<sup>1</sup> were prepared (Fig. 2). Alternatively, in the type II series, a 5-methyl-1,2,4-oxadiazole moiety was attached to position R<sup>1</sup> (Fig. 2). To the right-hand side of the type I and type II compounds illustrated in Fig. 2, different polar groups were introduced to form contacts with the Glu50–Arg76 salt bridge or with Arg136, such as terminal carboxylic or hydrazide groups. Additionally, as a slightly less acidic alternative for the carboxylic group, compounds with a 1,3,4-oxadiazole ring at R<sup>2</sup> or R<sup>3</sup> were prepared, with the aim of increasing the penetration of compounds into bacterial cells. In the type II series, a carbonyl group in the linker that connected the phenyl

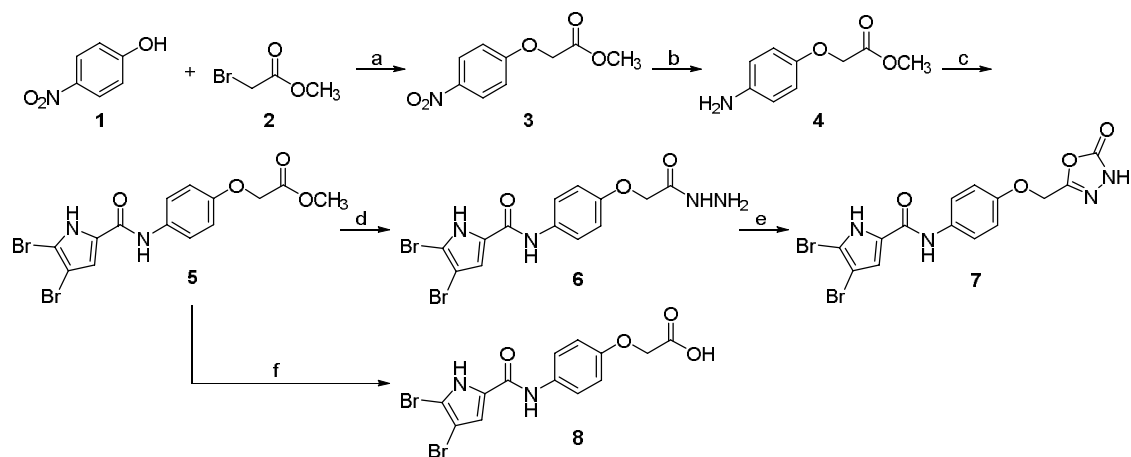
ring and the terminal acidic group was retained to form similar interactions with Glu50–Arg76 as the carbonyl group of inhibitor A (Fig. 2).



**Fig. 2** General structures of type I and type II compounds as potential DNA gyrase B inhibitors, designed using the X-ray structure of inhibitor A bound to *E. coli* GyrB (PDB code: 4ZVI)<sup>20</sup> as template.

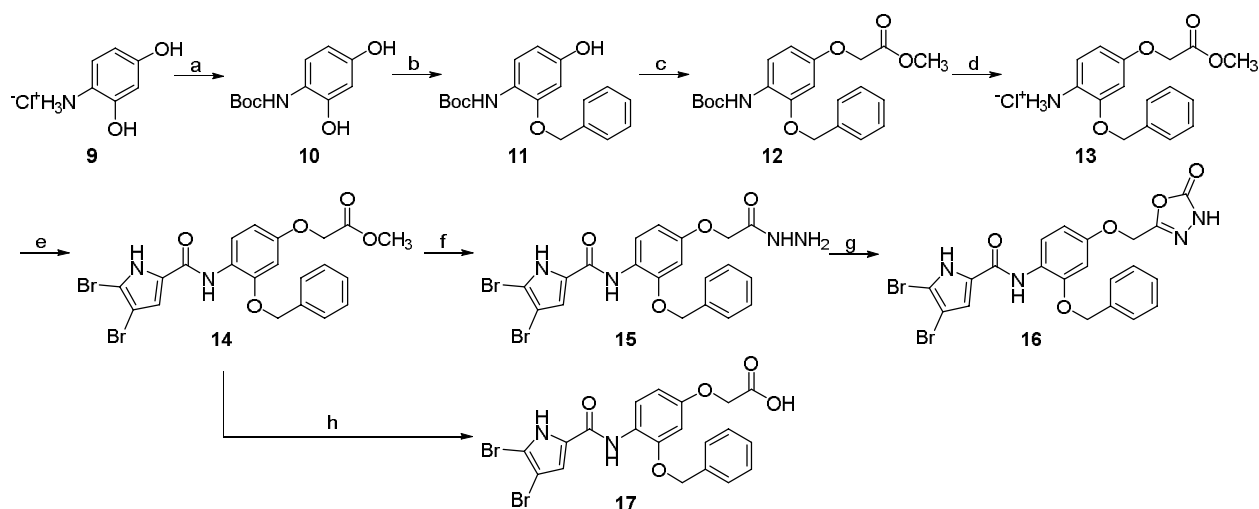
## 2.2. Chemistry

Type I compounds **5-7** were synthesised according to Scheme 1. The synthetic procedure and analytical data for compounds **5** and **8** were reported previously.<sup>20</sup> In the first step, 4-nitrophenol (**1**) was reacted with methyl 2-bromoacetate (**2**) to obtain compound **3**. The nitro group of **3** was then reduced to an amino group by catalytic hydrogenation, and in the next step, the *O*-(benzotriazol-1-yl)-*N,N,N',N'*-tetramethyluronium tetrafluoroborate (TBTU)-promoted coupling of the amine **4** with 4,5-dibromopyrrole-2-carboxylic acid afforded compound **5**. The final compound **7** was obtained using a two-step procedure; first the hydrazide **6** was formed using hydrazine monohydrate as the reagent, which was followed by a 1,1-carbonyldiimidazole-driven cyclisation and 1,3,4-oxadiazole ring formation.



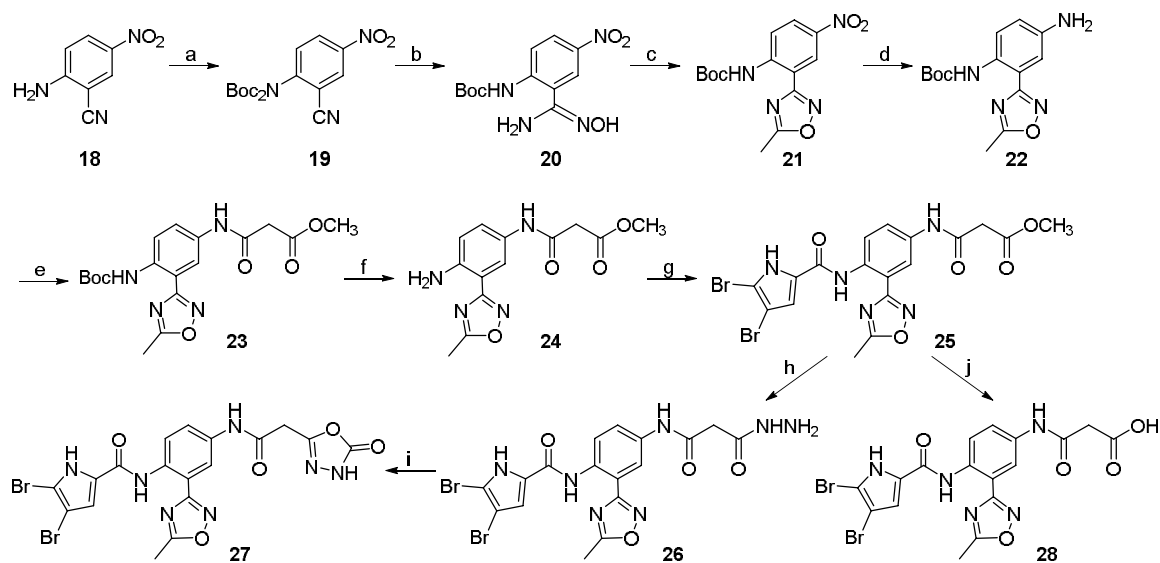
**Scheme 1.** Reagents and conditions: (a)  $\text{K}_2\text{CO}_3$ ,  $\text{CH}_3\text{CN}$ , rt, 15 h; (b)  $\text{H}_2$ , Pd/C, tetrahydrofuran, rt, 5 h; (c) 4,5-dibromo-pyrrole-2-carboxylic acid, TBTU, *N*-methylmorpholine,  $\text{CH}_2\text{Cl}_2$ , 50 °C, 15 h; (d) Hydrazine monohydrate, ethanol, 80 °C, 15 h; (e) 1,1-Carbonyldiimidazole, 1,4-dioxane, 101 °C, 15 h; (f) 2 M NaOH, tetrahydrofuran, rt, 15 h.

Type I compounds with benzyloxy substituents on the central benzene ring (**14-17**) were prepared according to Scheme 2 (see also Fig. 2, R<sup>1</sup>). First, the amino group of **9** was Boc protected, and the resulting compound **10** was then benzylated on the 2-OH group with benzyl bromide in the presence of potassium carbonate. The selective formation of the 2-benzyloxy derivative **11** was confirmed with <sup>1</sup>H-<sup>13</sup>C HSQC (heteronuclear single-quantum correlation spectroscopy) and <sup>1</sup>H-<sup>13</sup>C HMBC (heteronuclear multiple-bond correlation spectroscopy) nuclear magnetic resonance (Supplementary Information Fig. S1). Next, the 4-OH group of compound **11** was alkylated using methyl bromoacetate, to obtain **12**, after which the Boc protecting group was removed with gaseous hydrochloric acid, which resulted in compound **13**. 4,5-Dibromopyrrol-2-carboxylic acid was attached to the amino group of **13** using TBTU as coupling reagent to obtain **14**. The final compound **16** was synthesised first via the hydrazide formation, and then cyclisation to the 1,3,4-oxadiazole ring using 1,1-carbonyldiimidazole. Compound **17** was obtained by alkaline hydrolysis of the methyl ester group of **14**.



**Scheme 2.** Reagents and conditions: (a)  $\text{Boc}_2\text{O}$ ,  $\text{Et}_3\text{N}$ , methanol,  $0\text{ }^\circ\text{C} \rightarrow \text{rt}$ , 15 h; (b) Benzyl bromide,  $\text{K}_2\text{CO}_3$ ,  $\text{CH}_3\text{CN}$ ,  $0\text{ }^\circ\text{C} \rightarrow \text{rt}$ , 15 h; (c) Methyl bromoacetate,  $\text{K}_2\text{CO}_3$ ,  $\text{CH}_3\text{CN}$ ,  $0\text{ }^\circ\text{C} \rightarrow \text{rt}$ , 15 h; (d)  $\text{HCl}_{(\text{g})}$ , diethyl ether,  $\text{rt}$ , 15 h; (e) 4,5-Dibromo-pyrrole-2-carboxylic acid, TBTU, *N*-methylmorpholine,  $\text{CH}_2\text{Cl}_2$ ,  $50\text{ }^\circ\text{C}$ , 16 h; (f) Hydrazine monohydrate, ethanol,  $80\text{ }^\circ\text{C}$ , 15 h; (g) 1,1-Carbonyldiimidazole, 1,4-dioxane,  $101\text{ }^\circ\text{C}$ , 15 h; (h) 2 M  $\text{NaOH}$ , tetrahydrofuran,  $\text{rt}$ , 15 h.

Synthesis of the type II compounds **25–28** is presented in Scheme 3. The amino group of **18** was initially di-Boc protected with di-*tert*-butyl dicarbonate (2.5 equivalents) in the presence of triethylamine. In the next step, nucleophilic addition of hydroxylamine to the cyano group of **19** formed compound **20**. The *N*-hydroxycarbamimidoyl group of compound **20** was then cyclised to the 5-methyl-1,2,4-oxadiazole ring in the presence of acetic anhydride, to obtain compound **21**. Tin(II) chloride was used to reduce the nitro group of **21**, and the resulting amino group of **22** was acylated with methyl malonyl chloride in the presence of potassium carbonate, to obtain compound **23**. In the next step, the Boc protecting group was removed with 4 M hydrochloric acid in 1,4-dioxane, which resulted in compound **24**. The carboxylic group of 4,5-dibromopyrrole-2-carboxylic acid was then activated with oxalyl chloride and attached to **24**, to obtain the amide **25**. The final compound **27** was prepared in a two-step reaction, initially using hydrazine monohydrate to form the hydrazide **26**, and then 1,1-carbonyldiimidazole to form the 1,3,4-oxadiazole ring. To obtain compound **28**, the methyl ester group of **25** was removed under alkaline conditions.



**Scheme 3.** Reagents and conditions: (a)  $\text{Boc}_2\text{O}$ , DMAP,  $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CN}$ , 70 °C, 24 h; (b) Hydroxylamine hydrochloride,  $\text{Et}_3\text{N}$ , ethanol, 65 °C, 15 h; (c) Acetic anhydride, acetic acid, 85 °C, 15 h; (d) Tin(II) chloride, ethanol/ethyl acetate, 70 °C, 6 h; (e) Methyl malonyl chloride,  $\text{K}_2\text{CO}_3$ ,  $\text{CH}_3\text{CN}$ , 0 °C, 12 h; (f) 4 M HCl in 1,4-dioxane, rt, 15 h; (g) 4,5-Dibromo-pyrrole-2-carboxylic acid, oxalyl chloride,  $\text{CH}_2\text{Cl}_2$ , 15 h, then *ii*) **24**, pyridine,  $\text{CH}_2\text{Cl}_2$ , rt, 6 h; (h) Hydrazine monohydrate, ethanol/tetrahydrofuran, 80 °C, 15 h; (i) 1,1-Carbonyldiimidazole, 1,4-dioxane/dimethylformamide, 100 °C, 15 h; (j) 2 M NaOH, THF, rt, 15 h.

### 2.3. Biological data

The enzyme inhibition data against DNA gyrase from *E. coli* for all of the final compounds are given in Table 1, either as residual activities (RA) at 10  $\mu\text{M}$ , or as half-maximal inhibitory concentrations ( $\text{IC}_{50}$ ). The inhibitory data for compounds **5** and **8** were reported previously<sup>20</sup> and are included in Table 1 for comparison.

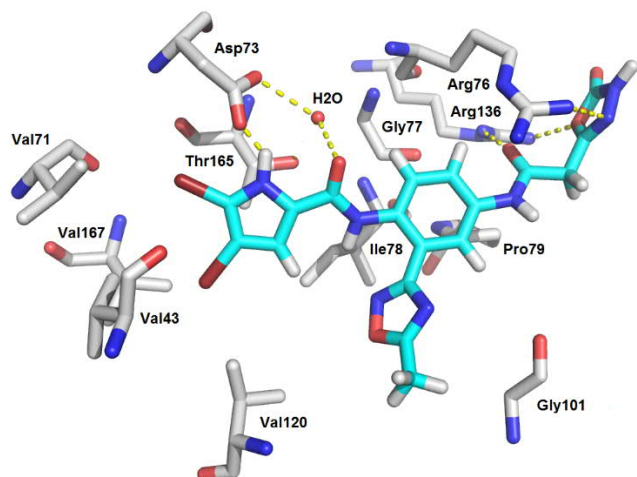
Compounds with carboxylic groups on  $\text{R}^2$  and  $\text{R}^3$  were more potent than their methyl ester precursors, probably because they can form stronger interactions with the Arg136 group. This can be seen by comparing compound **14**, with a  $\text{COOCH}_3$  group at  $\text{R}^2$  (RA, 100%) with compound **17**, with a carboxylic group at  $\text{R}^2$  ( $\text{IC}_{50}$ , 0.86  $\mu\text{M}$ ), or by comparing the methyl ester **25** ( $\text{IC}_{50}$  = 0.086  $\mu\text{M}$ ) with its carboxylic analogue **28** ( $\text{IC}_{50}$ , 0.020  $\mu\text{M}$ ). Similarly, compounds **15** (RA, 100%) and **26** ( $\text{IC}_{50}$ , 0.14  $\mu\text{M}$ ) with a hydrazide group attached to  $\text{R}^2$  and  $\text{R}^3$ , respectively, showed weaker

activities against the *E. coli* DNA gyrase compared to their carboxylic analogues. This is probably because they cannot form ionic interactions with Arg136. The inhibitory activities of compounds **7** (IC<sub>50</sub>, 8.6 μM), **16** (RA, 85%) and **27** (IC<sub>50</sub>, 0.045 μM), which contained a 1,3,4-oxadiazole ring as a bioisostere for the carboxylic group, were higher than the activities of their methyl ester or hydrazide analogues, although also slightly lower than the activities of the corresponding carboxylic acids. The NH proton of the 1,3,4-oxadiazole ring has a low pKa, and it can be deprotonated under the test conditions, which will result in stronger polar interactions of these compounds with Arg136, compared to their methyl esters and hydrazides, although they will have weaker interactions compared to compounds with carboxylic groups. The most potent inhibitor from the type I series was compound **17** (IC<sub>50</sub>, 0.86 μM), which contains a carboxylic group on R<sup>2</sup> and a benzyloxy substituent on the central phenyl ring (R<sup>1</sup>). The activity of compound **17** was approximately twice that of its analogue **8** without the benzyloxy substituent, which shows that relatively bulky lipophilic substituents can be tolerated at this position, and can form favourable interactions with the lipophilic floor of the enzyme. Interestingly, the inhibitory activity of compound **16** (RA, 85%) with a 1,3,4-oxadiazole ring on R<sup>2</sup> and a benzyloxy substituent on the phenyl ring (R<sup>1</sup>) was lower than the activity of its analogue **7** without the benzyloxy group (IC<sub>50</sub>, 8.6 μM).

Compounds of the type II series (**25-28**), which contain a 5-methyl-1,2,4-oxadiazole moiety attached to the central 4-aminoaniline ring (R<sup>1</sup> of type I series), were approximately 100 fold more potent than the type I compounds. Their IC<sub>50</sub> against *E. coli* DNA gyrase were in the low nanomolar range. The most potent compound from the type II series was compound **28**, with an IC<sub>50</sub> against *E. coli* DNA gyrase of 0.020 μM, and this was followed by its analogue **27** (IC<sub>50</sub>, 0.045 μM), with a 1,3,4-oxadiazole ring on R<sup>3</sup>. A possible reason for the higher activity of these type II compounds compared to the type I compounds is the 5-methyl-1,2,4-oxadiazole group, which can form hydrophobic or π-stacking interactions with the amino acid residues of the lipophilic floor of the enzyme. Another possible reason is additional polar interactions between the C=O group in the linker that connects the phenyl ring and the terminal acidic group, and the Glu50-Arg76 salt bridge, similar to those seen for the C=O group of inhibitor A in its crystal structure with *E. coli* GyrB (Fig. 2). We have shown the possibility of these interactions with docking of compound **27** into the GyrB active site (Fig. 3). Fig.3 additionally shows the possibility of interactions between the NH and O groups 1,3,4-oxadiazole ring of **27** and Arg76 or Arg136. Thus, overall, it appears that for

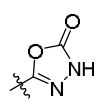
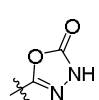



high activity against *E. coli* DNA gyrase, there is the need for a combination of a substituent that is directed towards the lipophilic floor of the enzyme, and a polar carboxylic group or its bioisostere on R<sup>2</sup> or R<sup>3</sup>, with a possible additional C=O or similar group in the linker.



**Fig. 3** Binding mode of compound **27** (cyan) in the *E. coli* GyrB (grey) (PDB code: 4DUH),<sup>25</sup> as predicted with GOLD.<sup>26</sup> The crystal water molecule is shown as a red sphere. The predicted H-bonds are given as yellow dotted lines. The Fig. was prepared using PyMOL.<sup>27</sup>

**Table 1.** Inhibitory activities of the type I and type II compounds against DNA gyrase from *E. coli*.

Compound	Type	R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	IC <sub>50</sub> (μM) <sup>a</sup> or RA (%) <sup>b</sup>
<b>5</b> <sup>c</sup>	I	H	COOCH <sub>3</sub>	-	IC <sub>50</sub> = 88 ± 19
<b>6</b>	I	H	CONHNH <sub>2</sub>	-	RA = 100
<b>7</b>	I	H		-	IC <sub>50</sub> = 8.6 ± 2.4
<b>8</b> <sup>c</sup>	I	H	COOH	-	IC <sub>50</sub> = 1.4 ± 0.2
<b>14</b>	I	OBzl	COOCH <sub>3</sub>	-	RA = 100
<b>15</b>	I	OBzl	CONHNH <sub>2</sub>	-	RA = 100
<b>16</b>	I	OBzl		-	RA = 85

<b>17</b>	I	OBzl	COOH	-	IC <sub>50</sub> = 0.86 ± 0.02
<b>25</b>	II	-	-	COOCH <sub>3</sub>	IC <sub>50</sub> = 0.086 ± 0.011
<b>26</b>	II	-	-	CONHNH <sub>2</sub>	IC <sub>50</sub> = 0.14 ± 0.02
<b>27</b>	II	-	-		IC <sub>50</sub> = 0.045 ± 0.022
<b>28</b>	II	-	-	COOH	IC <sub>50</sub> = 0.020 ± 0.009
Novobiocin					IC <sub>50</sub> = 0.17 ± 0.02

<sup>a</sup> Concentration of compound that inhibits the enzyme activity by 50%. <sup>b</sup> Residual activity of the enzyme at 10 μM concentration of the compound. <sup>c</sup> Previously published results.<sup>20</sup>

Selected compounds were also tested against DNA gyrase from *Staphylococcus aureus* and against topoisomerase IV from *E. coli* and *S. aureus*. The inhibitory activities against those three enzymes were lower in comparison with *E. coli* DNA gyrase, probably because of the comparatively smaller sizes of the adenine binding pockets of these enzymes, which do not fit the large dibromopyrrole moiety perfectly.<sup>15</sup> The most potent compound was again compound **28**, with an IC<sub>50</sub> of 1.4 μM against *S. aureus* DNA gyrase, 11 μM against *E. coli* topoisomerase IV, and 14 μM against *S. aureus* topoisomerase IV (Table 2).

**Table 2.** Inhibitory activities of selected compounds against DNA gyrase from *S. aureus* and topoisomerase IV from *E. coli* and *S. aureus*.

Compound	IC <sub>50</sub> (μM) <sup>a</sup> or RA (%) <sup>b</sup>		
	<i>S. aureus</i> DNA gyrase	<i>E. coli</i> topoisomerase IV	<i>S. aureus</i> topoisomerase IV
<b>8</b> <sup>c</sup>	RA = 88	RA = 91	RA = 100
<b>17</b>	RA = 87	RA = 84	RA = 92
<b>25</b>	IC <sub>50</sub> = 63 ± 14	RA = 72	RA = 100
<b>26</b>	RA = 80	RA = 88	RA = 98
<b>27</b>	IC <sub>50</sub> = 11 ± 2	RA = 91	RA = 60
<b>28</b>	IC <sub>50</sub> = 1.4 ± 0.4	IC <sub>50</sub> = 11 ± 3	IC <sub>50</sub> = 14 ± 4
Novobiocin	IC <sub>50</sub> = 0.041 ± 0.007	IC <sub>50</sub> = 11 ± 2	IC <sub>50</sub> = 27 ± 7

<sup>a</sup> Concentration of compound that inhibits the enzyme activity by 50%. <sup>b</sup> Residual activity of the enzyme at 10 μM concentration of the compound. <sup>c</sup> Previously published results.<sup>20</sup>

Compounds **7**, **16**, **17** and **25-28** that were the most potent in the enzymatic assay, were evaluated for their antibacterial activities against two Gram-positive bacterial strains (*Enterococcus faecalis* American Type Culture Collection [ATCC] 29212 and *S. aureus* ATCC 25923) and two Gram-

negative bacterial strains (*E. coli* ATCC 25922 and *Pseudomonas aeruginosa* ATCC 27853). These data are given in Supplementary Information Table S1, and they are expressed as percentage inhibition of bacteria growth at 50  $\mu$ M, for each tested compound. None of the tested compounds showed any particular inhibition of the bacterial strains used. The most active compound against *E. faecalis* was compound **17** with 25% inhibition, and the best compound against *E. coli* was **26** with 16% inhibition. The most probable reason for the lack of antibacterial activity is low intracellular concentration of compounds, which can be due to (i) insufficient penetration of compounds through the bacterial cell envelope, or (ii) active efflux of inhibitors because of efflux pumps. Additionally, for the higher antibacterial activity, probably also the on-target activities should be slightly improved.

### **3. Experimental section**

#### **3.1. Determination of inhibitory activities on DNA gyrase and topoisomerase IV**

The assays for the IC<sub>50</sub> determinations were performed according to previously reported procedures.<sup>21</sup>

#### **3.2. Determination of antibacterial activity**

Clinical control strains of *E. faecalis* (Gram positive; ATCC 29212), *E. coli* (Gram negative; ATCC 25922), *P. aeruginosa* (Gram negative; ATCC 27853), and *S. aureus* (Gram positive; ATCC 25923) were obtained from Microbiologics Inc. (St. Cloud, Minnesota, USA). Bacterial cultures were initiated on cation-adjusted Mueller Hinton agar (Becton Dickinson, Franklin Lakes, NJ, USA) slants, and prior to the assays, the suspensions were prepared in cation-adjusted Mueller Hinton broth (Becton Dickinson, Franklin Lakes, NJ, USA) and incubated at 37 °C for 16 h to 20 h at 100 rpm. Antimicrobial assays were performed by the broth microdilution method, in a 96-well plate format, according to the Clinical and Laboratory Standards Institute guidelines<sup>28</sup> and to previously reported procedures.<sup>21</sup>

#### **3.3. Molecular modelling**

Protein and ligand preparation and ligand docking were performed using GOLD Suite v5.4,<sup>29</sup> according to the previously reported procedures<sup>22</sup> and are described in Supplementary Information.

### 3.4. Chemistry

Chemicals were obtained from Acros Organics (Geel, Belgium), Sigma-Aldrich (St. Louis, MO, USA) and Apollo Scientific (Stockport, UK), and they were used without further purification. Analytical TLC was performed on silica gel Merck 60 F<sub>254</sub> plates (0.25 mm), with visualisation with UV light and spray reagents. Column chromatography was carried out on silica gel 60 (particle size 240-400 mesh). HPLC analyses were performed on a 1100 system (Agilent Technologies, Santa Clara, CA, USA) with a UV-Vis detector (G1365B), a thermostat (G1316A) and an autosampler (G1313A). A C18 column was used (Phenomenex Luna 5  $\mu$ m, 4.6  $\times$  150 mm), with a flow rate of 1.0 mL/min. The eluent consisted of trifluoroacetic acid (0.1% in water) as solvent A and acetonitrile as solvent B. Melting points were determined on a Reichert hot stage microscope, and are uncorrected. <sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded at 400 MHz and 100 MHz, respectively, on an AVANCE III 400 spectrometer (Bruker Corporation, Billerica, MA, USA) in DMSO-*d*<sub>6</sub> or CDCl<sub>3</sub>, with TMS as the internal standard. The infrared spectra were recorded on a Fourier-transform infrared spectrometer (Thermo Nicolet Nexus 470 ESP; Thermo Fisher Scientific, Waltham, MA, USA). Mass spectra were obtained using a mass spectrometer (Q-TOF Premier; Micromass, Waters, Manchester, UK). The purity of the tested compounds was  $\geq$ 95%, as established by HPLC.

### 3.5. Synthetic procedures

**Methyl 2-(4-nitrophenoxy)acetate (3).** To a suspension of 4-nitrophenol (**1**, 1.50 g, 11.0 mmol) and potassium carbonate (1.52 g, 11.0 mmol) in acetonitrile (50 mL) methyl bromoacetate (**2**, 1.05 mL, 11.0 mmol) was added dropwise. The reaction mixture was stirred overnight at rt. Solvent was evaporated under reduced pressure and the solid residue was dissolved in ethyl acetate (100 mL). The organic phase was washed with water (2  $\times$  20 mL) and brine (20 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and evaporated under reduced pressure. Yield: 80%; white crystals (2.12 g); mp: 98-100 °C (98-99 °C)<sup>30</sup>; R<sub>f</sub> (dichloromethane/methanol = 10/1): 0.84; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  3.72 (s, 3H, CH<sub>3</sub>), 5.02 (s, 2H, CH<sub>2</sub>), 7.12 (d, 2H, *J* = 9.2 Hz, Ar-H-2, 6), 8.21 (d, 2H, *J* = 9.2 Hz, Ar-H-3,5); IR (ATR)  $\nu$  = 3402, 3313, 3116, 2956, 1756, 1722, 1610, 1592, 1498, 1436, 1330, 1198, 1173, 1110, 1000, 856, 752 cm<sup>-1</sup>.

**Methyl 2-(4-aminophenoxy)acetate (4).** Compound **3** (2.07 g) was dissolved in tetrahydrofuran (50 mL) and Pd/C (0.414 g) was added. The reaction was stirred under H<sub>2</sub> atmosphere for 5 h, the

catalyst was filtered off and the solvent was removed under reduced pressure, to obtain **4** (1.73 g) as a yellow oil. Yield: 96%; yellow oil (1.73 g); mp: 215-217 °C; Rf (dichloromethane/methanol = 10/1): 0.29; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 3.68 (s, 3H, CH<sub>3</sub>), 4.60 (s, 2H, CH<sub>2</sub>), 4.68 (s, 2H, NH<sub>2</sub>), 6.49-6.51(m, 2H, Ar-H-2,6), 6.65 (d, 2H, *J* = 9.2 Hz, Ar-H-3, 5); IR (ATR)  $\nu$  = 3456, 3434, 3359, 3046, 2953, 2922, 2856, 1748, 1509, 1440, 1214, 826 cm<sup>-1</sup>.

**General procedure A. Synthesis of compounds 5 and 14 (compound 5 is given as an example).**

A solution of 4,5-dibromo-pyrrole-2-carboxylic acid (245 mg, 0.911 mmol), TBTU (319 mg, 0.993 mmol) and *N*-methylmorpholine (273  $\mu$ L, 2.48 mmol) in dichloromethane (20 mL) was stirred at rt for 30 min. Compound **3** (144 mg, 0.69 mmol) was added and the mixture was stirred at 50 °C overnight. The solvent was removed under reduced pressure, the residue was dissolved in ethyl acetate (20 mL) and the organic phase was washed with water (2  $\times$  10 mL), brine (2  $\times$  10 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was removed under reduced pressure. To the crude product ether (10 mL) was added, the obtained suspension was sonicated and the undissolved solid was filtered off, washed with ether and dried.

**Methyl 2-(4-(4,5-dibromo-1*H*-pyrrole-2-carboxamido)phenoxy)acetate (5).** Compound was prepared according to general procedure A. Yield: 46%; yellow crystals (165 mg); mp: 190-192 °C; Rf (ethyl acetate/petroleum ether = 1/2): 0.42; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 3.71 (s, 3H, CH<sub>3</sub>), 4.78 (s, 2H, CH<sub>2</sub>), 6.92-6.94 (m, 2H, Ar-H-2,6), 7.19 (s, 1H, pyrrole-CH), 7.60 (d, 2H, *J* = 9.2 Hz, Ar-H-3,5), 9.77 (s, 1H, NH), 12.88 (s, 1H, pyrrole-NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 51.77 (CH<sub>3</sub>), 64.71 (CH<sub>2</sub>), 98.03, 105.55, 113.44, 114.55, 121.49, 127.97, 132.38, 153.67, 157.07, 169.29; IR (ATR)  $\nu$  = 3388, 3300, 3204, 2955, 2852, 1757, 1730, 1650, 1553, 1525, 1509, 1417, 1389, 1223, 1177, 1078, 973, 820, 750 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 428.9 ([M-H]<sup>-</sup>). HRMS for C<sub>14</sub>H<sub>11</sub>N<sub>2</sub>O<sub>4</sub>Br<sub>2</sub>: calculated 428.9086; found 428.9088; HPLC: t<sub>R</sub> = 19.554 min (98.6% at 280 nm).

**General procedure B. Synthesis of compounds 6, 15 and 26 (compound 6 is given as an example).** Compound **5** (670 mg, 1.55 mmol) and hydrazine monohydrate (0.754 mL, 15.5 mmol) were dissolved in ethanol (10 mL) and the mixture was stirred at 80 °C overnight. The reaction mixture was cooled on an ice bath and the white precipitate was filtered off, washed with ethanol and dried to obtain **6** as white crystals (0.565 mg).

**4,5-Dibromo-N-(4-(2-hydrazineyl-2-oxoethoxy)phenyl)-1H-pyrrole-2-carboxamide (6).**

Compound was prepared according to general procedure B. Yield: 84%; white crystals (0.565 g); mp: 257-259 °C; R<sub>f</sub> (dichloromethane/methanol = 20/1): 0.12; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 4.37 (br s, 2H, NH<sub>2</sub>), 4.47 (s, 2H, CH<sub>2</sub>), 6.95 (d, 2H, *J* = 9.2 Hz, Ar-H), 7.19 (s, 1H, pyrrol-CH), 7.59 (d, 2H, *J* = 9.2 Hz, Ar-H), 9.34 (s, 1H, NH), 9.77 (s, 1H, NH), 12.87 (s, 1H, pyrrol-NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>) δ 66.46 (CH<sub>2</sub>), 98.02, 105.54, 113.43, 114.70, 121.46, 12.99, 132.28, 153.93, 157.07, 166.67; IR (ATR)  $\nu$  = 3436, 3303, 3119, 3072, 2950, 2861, 2687, 1649, 1605, 1512, 1419, 1391, 1224, 1075, 831 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 429.0 ([M-H]<sup>-</sup>). HRMS for C<sub>13</sub>H<sub>11</sub>N<sub>4</sub>O<sub>3</sub>Br<sub>2</sub>: calculated 428.9198; found 428.9201; HPLC: t<sub>R</sub> = 5.843 min (96.4% at 280 nm).

**General procedure C. Synthesis of compounds 7, 16 and 27 (compound 7 is given as an example).** Compound 7 (150 mg, 0.35 mmol) and 1,1-carbonyldiimidazole (85 mg, 0.52 mmol) were suspended in 1,4-dioxane (15 mL), and the reaction mixture was heated at 101 °C overnight. The solvent was evaporated under reduced pressure and the solid residue was purified using column chromatography (dichloromethane/methanol = 20/1), to obtain 7 as white solid (71 mg).

**4,5-Dibromo-N-(4-((5-oxo-4,5-dihydro-1,3,4-oxadiazol-2-yl)methoxy)phenyl)-1H-pyrrole-2-carboxamide (7).** Compound was prepared according to general procedure C. Yield: 45%; white solid (71 mg); mp: 260-262 °C; R<sub>f</sub> (dichloromethane/methanol= 20/1): 0.17; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 5.04 (s, 2H, CH<sub>2</sub>), 7.04 (d, 2H, *J* = 8.8 Hz, Ar-H), 7.20 (s, 1H, pyrrole-CH), 7.63 (d, 2H, *J* = 8.8 Hz, Ar-H), 9.80 (s, 1H, NH), 12.53 (s, 1H, NH), 12.89 (s, 1H, pyrrole-NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>) δ 60.69 (CH<sub>2</sub>), 98.05, 105.63, 113.50, 115.12, 121.44, 127.94, 132.94, 152.92, 153.28, 154.60, 157.10; IR (ATR)  $\nu$  = 3344, 3205, 1775, 1745, 1641, 1605, 1553, 1524, 1508, 1414, 1385, 1334, 1299, 1222, 1171, 1093, 939, 820, 742, 656; MS (ESI) *m/z* (%) = 455.0 ([M-H]<sup>-</sup>). HRMS for C<sub>14</sub>H<sub>9</sub>N<sub>4</sub>O<sub>4</sub>Br<sub>2</sub>: calculated 454.8991; found 454.8980; HPLC: t<sub>R</sub>: 9.517 min (98.1% at 280 nm).

**General procedure D. Synthesis of compounds 8, 17, 28 (compound 28 is given as an example).** To a solution of compound 25 (51 mg, 0.096 mmol) in tetrahydrofuran (6 mL) 2 M NaOH (145 μL, 0.29 mmol) and water (2 mL) were added. The reaction mixture was stirred overnight at room temperature and neutralized with 1M HCl. Solvent was removed under reduced pressure and the residue was dissolved in ethyl acetate (10 mL). Organic phase was washed with

1M HCl ( $2 \times 7$  mL), saturated solution of NaHCO<sub>3</sub> ( $2 \times 30$  mL), brine (7 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was removed under reduced pressure, to obtain **28** as grey solid (32 mg).

**2-(4-(4,5-Dibromo-1H-pyrrole-2-carboxamido)phenoxy)acetic acid (8).** Compound was prepared according to general procedure D. Reported previously.<sup>20</sup>

**tert-Butyl (2,4-dihydroxyphenyl)carbamate (10).** To a solution of 2,4-dihydroxybenzenaminium chloride (**9**, 2.75 g, 17.1 mmol) and triethylamine (2.61 mL, 18.7 mmol) in glacial acetic acid (100 mL) cooled on an ice bath, a solution of di-*tert*-butyl dicarbonate (5.57 g, 25.5 mmol) in methanol (5 mL) was added dropwise. The reaction mixture was stirred overnight at rt, the solvent was removed under reduced pressure and the residue was dissolved in ethyl acetate (100 mL). Organic phase was washed with water ( $2 \times 30$  mL), 10% citric acid ( $2 \times 30$  mL) and brine ( $2 \times 30$  mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was removed under reduced pressure. The crude product was purified with flash column chromatography (dichloromethane/methanol = 20/1) to obtain **10** (2.51 g) as a dark oil. Yield, 68%; dark oil (2.51 g); R<sub>f</sub> (dichloromethane/methanol = 20/1): 0.16; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  1.43 (s, 9H, 3  $\times$  CH<sub>3</sub>), 6.14-6.17 (m, 1H, Ar-H-5), 6.30 (d, 1H, *J* = 2.8 Hz, Ar-H-3), 7.14 (d, 1H, *J* = 8.4 Hz, Ar-H-6), 7.66 (s, 1H, NH), 9.04 (s, 1H, OH), 9.40 (s, 1H, OH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  28.11 (3  $\times$  CH<sub>3</sub>), 78.46, 102.71, 105.57, 117.58, 123.88, 149.74, 153.59, 154.45; IR (ATR)  $\nu$  = 3307, 2979, 2934, 1680, 1609, 1523, 1452, 1368, 1284, 1246, 1152, 1112, 1054, 971, 841, 802, 732 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 224.1 ([M-H]<sup>-</sup>). HRMS for C<sub>11</sub>H<sub>14</sub>NO<sub>4</sub>: calculated 224.0923; found 224.0922.

**tert-Butyl (2-(benzyloxy)-4-hydroxyphenyl)carbamate (11).** To a suspension of compound **10** (2.50 g, 11.9 mmol) and potassium carbonate (3.29 g, 23.7 mmol) in acetonitrile (100 mL) benzyl bromide (1.41 mL, 11.9 mmol) was added dropwise at 0 °C, and the reaction mixture was stirred overnight at rt. Solvent was removed under reduced pressure and the solid residue was dissolved in ethyl acetate (100 mL). The organic phase was washed with water ( $3 \times 20$  mL), saturated solution of NaHCO<sub>3</sub> ( $2 \times 20$  mL) and brine (20 mL), dried with Na<sub>2</sub>SO<sub>4</sub>, and the solvent was removed under reduced pressure. The crude product was purified with column chromatography (dichloromethane/ethyl acetate = 20/1) to obtain **11** (1.30 g) as a white solid. Yield: 36%; white solid (1.30 g); mp: 135-136 °C; R<sub>f</sub> (dichloromethane/ethyl acetate = 20/1): 0.20; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  1.42 (s, 9H, 3  $\times$  CH<sub>3</sub>), 5.06 (s, 2H, CH<sub>2</sub>), 6.28-6.31 (m, 1H, Ar-H-5), 6.30 (d, 1H, *J* = 2.8 Hz, Ar-H-3), 7.16 (d, 1H, *J* = 8.8 Hz, Ar-H-6), 7.33-7.40 (m, 3H, 3  $\times$  Ar-H), 7.47-7.49 (m,

2H, 2 × Ar-H), 7.83 (s, 1H, NH), 9.29 (s, 1H, OH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 28.12 (3 × CH<sub>3</sub>), 69.30 (CH<sub>2</sub>), 78.29, 100.68, 106.43, 118.69, 125.44, 127.37, 127.69, 128.28, 137.10, 151.99, 153.68, 155.14; IR (ATR)  $\nu$  = 3358, 3289, 3032, 2979, 1680, 1597, 1524, 1507, 1457, 1363, 1281, 1242, 1177, 1153, 1107, 1013, 974, 832, 702, 628 cm<sup>-1</sup>; MS (ESI)  $m/z$  (%) = 314.1 ([M-H]<sup>-</sup>). HRMS for C<sub>18</sub>H<sub>20</sub>NO<sub>4</sub>: calculated 314.1392; found 314.1401.

**Methyl 2-(3-(benzyloxy)-4-((*tert*-butoxycarbonyl)amino)phenoxy)acetate (12).** To a suspension of compound **11** (500 mg, 1.63 mmol) and potassium carbonate (450 mg, 3.25 mmol) in acetonitrile (20 mL) methyl bromoacetate (155  $\mu$ L, 1.63 mmol) was added dropwise at 0 °C, and the reaction mixture was stirred overnight at rt. Solvent was removed under reduced pressure and the solid residue was dissolved in ethyl acetate (20 mL). The organic phase was washed with water (3 × 10 mL), saturated solution of NaHCO<sub>3</sub> (2 × 10 mL) and brine (10 mL), dried with Na<sub>2</sub>SO<sub>4</sub>, and the solvent was removed under reduced pressure to obtain **12** (0.610 g) as a yellow solid. Yield: 99%; yellow solid (610 mg); Mp: 101-103 °C; R<sub>f</sub> (dichloromethane/methanol = 20/1): 0.79; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 1.43 (s, 9H, 3 × CH<sub>3</sub>), 3.69 (s, 3H, CH<sub>3</sub>), 4.75 (s, 2H, CH<sub>2</sub>), 5.13 (s, 2H, CH<sub>2</sub>), 6.30-6.46 (m, 1H, Ar-H-5), 6.68 (d, 1H, *J* = 2.4 Hz, Ar-H-3), 7.31-7.41 (m, 4H, 4 × Ar-H-), 7.50-7.51 (m, 2H, 2 × Ar-H), 7.96 (s, 1H, NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 28.09 (3 × CH<sub>3</sub>), 51.75 (CH<sub>3</sub>), 64.60 (CH<sub>2</sub>), 69.59 (CH<sub>2</sub>), 78.60, 100.82, 104.93, 121.10, 124.67, 127.50, 127.78, 128.32, 136.91, 151.54, 153.46, 155.06, 169.18; IR (ATR)  $\nu$  = 3431, 3061, 3033, 2981, 2957, 1753, 1718, 1617, 1521, 1485, 1429, 1364, 1243, 1165, 1127, 1009, 826, 773, 701 cm<sup>-1</sup>; MS (ESI)  $m/z$  (%) = 388.2 ([M-H]<sup>+</sup>). HRMS for C<sub>21</sub>H<sub>26</sub>NO<sub>6</sub>: calculated 388.1760; found 388.1767.

**2-(Benzyloxy)-4-(2-methoxy-2-oxoethoxy)benzenaminium chloride (13).** Compound **12** (0.550 g, 1.45 mmol) was dissolved in diethyl ether (20 mL), HCl(g) was bubbled through the solution for 40 min and the reaction mixture was stirred overnight at rt. Precipitated crystals were filtered off, washed with cold diethyl ether (2 × 10 mL) and dried. Yield: 42%; white crystals (185 mg); mp: 199-200 °C; R<sub>f</sub> (ethyl acetate/petroleum ether = 1/1): 0.55; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 3.69 (s, 3H, CH<sub>3</sub>), 4.84 (s, 2H, CH<sub>2</sub>), 5.25 (s, 2H, CH<sub>2</sub>), 6.58-6.60 (m, 1H, Ar-H-5), 6.87 (d, 1H, *J* = 2.4 Hz, Ar-H-3), 7.40-7.44 (m, 4H, 4 × Ar-H), 7.57-7.59 (m, 2H, 2 × Ar-H), 7.91 (s, 3H, NH<sub>3</sub><sup>+</sup>); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 51.84 (CH<sub>3</sub>), 64.77 (CH<sub>2</sub>), 69.94 (CH<sub>2</sub>), 101.38, 105.70, 114.11, 124.49, 127.67, 127.99, 128.38, 136.16, 152.16, 158.08, 168.88; IR (ATR)  $\nu$  = 2846, 2623, 2588,



1744, 1633, 1506, 1448, 1304, 1234, 1200, 1165, 1067, 997, 834, 751  $\text{cm}^{-1}$ ; MS (ESI)  $m/z$  (%) = 288.1 ( $[\text{M}-\text{H}]^+$ ). HRMS for  $\text{C}_{16}\text{H}_{18}\text{NO}_4$ : calculated 288.1236; found 288.1241.

***tert*-Butyl-(1-(*tert*-butyloxy)carbonyl)(2-cyano-4-nitrophenyl)carbamate (19).** To a solution of 2-amino-5-nitrobenzotrile (18, 3.00 g, 18.4 mmol) in a mixture of dichloromethane (30 mL) and acetonitrile (30 mL) di-*tert*-butyl dicarbonate (10.0 g, 45.8 mmol) and DMAP (50.0 g, 0.41 mol) were added and the mixture was heated at 70 °C for 24 h. The solvent was evaporated and the solid residue was dissolved in ethyl acetate (50 mL). Organic phase was washed with water (2 × 20 mL), saturated solution of  $\text{NaHCO}_3$  (2 × 20 mL), 0.5 M HCl (2 × 20 mL) and brine (2 × 20 mL), dried over  $\text{Na}_2\text{SO}_4$  and the solvent was removed under reduced pressure. The crude product was purified by crystallization from diethyl ether (30 mL). Yield: 40%; pale yellow crystals (5.2 g); mp: 87-88 °C;  $R_f$  (dichloromethane/petroleum ether = 8/2): 0.19;  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO}-d_6$ )  $\delta$  1.39 (s, 18H, 2 ×  $\text{C}(\text{CH}_3)_3$ ), 7.93-7.95 (d, 1H,  $J = 8.8$  Hz, Ar-H-6), 8.57-8.60 (dd, 1H,  $J_1 = 8.8$  Hz,  $J_2 = 2.4$  Hz, Ar-H-5), 8.90 (d,  $J = 2.44$  Hz, 1H, Ar-H-3);  $^{13}\text{C}$  NMR (100 MHz,  $\text{DMSO}-d_6$ ):  $\delta$  27.30 ( $\text{C}(\text{CH}_3)_3$ ), 84.01 ( $\text{C}(\text{CH}_3)_3$ ), 112.93, 114.34, 128.48, 129.01, 131.29, 146.58, 146.71, 149.08; IR (ATR)  $\nu = 3080, 2978, 2936, 2237, 1798, 1529, 1368, 1347, 1276, 1254, 1150, 1095, 845, 832, 786, 776$   $\text{cm}^{-1}$ ; MS (ESI)  $m/z$  (%) = 362.1 ( $[\text{M}-\text{H}]^-$ ).

***tert*-Butyl (*E*)-(2-(*N'*-hydroxycarbamimidoyl)-4-nitrophenyl)carbamate (20).** To a solution of compound 19 (4.00 g, 11.0 mmol) in absolute ethanol (50 mL), hydroxylamine hydrochloride (2.29 g, 33.0 mmol) and triethylamine (6.10 mL, 44.0 mmol) were added. The reaction mixture was heated overnight at 65 °C. The solvent was evaporated and the solid residue was dissolved in ethyl acetate (50 mL). Organic phase was washed with water (2 × 20 mL), saturated solution of  $\text{NaHCO}_3$  (2 × 20 mL), 0.5 M HCl (2 × 20 mL) and brine (2 × 20 mL), dried with  $\text{Na}_2\text{SO}_4$  and the solvent was removed under reduced pressure. Yield: 53%; pale yellow solid (3.33 g); mp: 155-156 °C;  $R_f$  (dichloromethane/methanol = 20/1): 0.60;  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO}-d_6$ )  $\delta$  1.50 (s, 9H,  $\text{C}(\text{CH}_3)_3$ ), 6.44 (s, 2H,  $\text{NH}_2$ ), 8.23-8.26 (m, 1H, Ar-H), 8.45-8.51 (m, 2H, 2 × Ar-H), 10.36 (s, 1H, OH/NH), 11.16 (s, 1H, OH/NH);  $^{13}\text{C}$  NMR (100 MHz,  $\text{DMSO}-d_6$ ):  $\delta$  27.82 ( $\text{C}(\text{CH}_3)_3$ ), 80.96 ( $\text{C}(\text{CH}_3)_3$ ), 118.00, 118.79, 123.36, 124.88, 140.93, 143.18, 151.02, 151.80; IR (ATR)  $\nu = 3367, 2982, 1735, 1597, 1497, 1368, 1339, 1309, 1233, 1131, 900, 827, 771, 747, 706$   $\text{cm}^{-1}$ ; MS (ESI)  $m/z$  (%) = 297.1 ( $[\text{M}-\text{H}]^+$ ).

**tert-Butyl (2-(5-methyl-1,2,4-oxadiazol-3-yl)-4-nitrophenyl)carbamate (21).** Compound 20 (2.86 g, 9.65 mmol) was dissolved in glacial acetic acid (30 mL), acetic anhydride was added (1.37 mL, 14.5 mmol) and the mixture was heated overnight at 85 °C. The solvent was evaporated and the solid residue was dissolved in ethyl acetate (40 mL). Organic phase was washed with water (2 × 20 mL), saturated solution of NaHCO<sub>3</sub> (2 × 20 mL), 0.5 M HCl (2 × 20 mL) and brine (2 × 20 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was evaporated under reduced pressure. The crude product was purified with flash column chromatography (ethyl acetate/petroleum ether = 1/8 to 1/4). Yield: 37%; yellow solid (1.6 g); mp: 139-142 °C; R<sub>f</sub> (ethyl acetate/petroleum ether = 1/4): 0.50; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 1.52 (s, 9H, C(CH<sub>3</sub>)<sub>3</sub>), 2.76 (s, 3H, CH<sub>3</sub>), 8.42 (dd, 1H, *J*<sub>1</sub> = 9.2 Hz, *J*<sub>2</sub> = 2.8 Hz, Ar-H), 8.50 (d, 1H, *J* = 9.2 Hz, Ar-H), 8.81 (d, 1H, *J* = 2.8 Hz, Ar-H-3), 9.83 (s, 1H, NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 11.98 (CH<sub>3</sub>), 27.73 (C(CH<sub>3</sub>)<sub>3</sub>), 81.69 (C(CH<sub>3</sub>)<sub>3</sub>), 113.75, 119.23, 124.80, 127.26, 141.45, 143.30, 151.51, 165.68, 177.35; IR (ATR) ν = 3293, 3076, 2977, 1725, 1579, 1547, 1512, 1341, 1284, 1237, 1131, 1048, 1025, 871, 852, 765, 683, 640 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 221.1 ([M-H]<sup>+</sup>).

**tert-Butyl (4-amino-2-(5-methyl-1,2,4-oxadiazol-3-yl)phenyl)carbamate (22).** To a solution of compound 21 (1.32 g, 4.11 mmol) in a mixture of ethanol (25 mL) and ethyl acetate (25 mL) tin(II) chloride (3.89 g, 20.5 mmol) was added and the reaction mixture was heated at 70 °C for 6 h. Saturated solution of sodium hydrogen phosphate (20 mL) was added and the mixture was heated at 70 °C for an additional hour. Solvent was evaporated and the solid residue was dissolved in ethyl acetate (30 mL). Organic phase was washed with water (2 × 20 mL) and brine (20 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was evaporated under reduced pressure. The crude product was purified with flash column chromatography (ethyl acetate/petroleum ether = 1/2). Yield: 82%; white solid (1.08 g); mp: 154-155 °C; R<sub>f</sub> (ethyl acetate/petroleum ether = 1/1): 0.42; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 1.43 (s, 9H, C(CH<sub>3</sub>)<sub>3</sub>), 2.76 (s, 3H, CH<sub>3</sub>), 5.20 (s, 2H, NH<sub>2</sub>), 6.72 (dd, 1H, *J*<sub>1</sub> = 8.8 Hz, *J*<sub>2</sub> = 2.8 Hz, Ar-H-5), 7.24 (d, 1H, *J* = 2.8 Hz, Ar-H-3), 7.57-7.59 (m, 1H, Ar-H-6), 8.76 (s, 1H, NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 11.30 (CH<sub>3</sub>), 28.05 (C(CH<sub>3</sub>)<sub>3</sub>), 78.93 (C(CH<sub>3</sub>)<sub>3</sub>), 113.60 (2 × C, overlapping signals), 117.25, 123.45, 126.33, 144.96, 152.88, 167.26, 176.18; IR (ATR) ν = 3432, 3357, 2978, 2932, 2360, 2340, 1713, 1528, 1525, 1513, 1296, 1281, 1246, 1231, 1156, 1056, 879, 764, 662 cm<sup>-1</sup>; MS (ESI) *m/z*(%) = 291.1 ([M-H]<sup>+</sup>), HRMS for C<sub>14</sub>H<sub>19</sub>N<sub>4</sub>O<sub>3</sub>: calculated 291.1457, found 291.1452.

**Methyl 3-((4-((*tert*-butoxycarbonyl)amino)-3-(5-methyl-1,2,4-oxadiazol-3-yl)phenyl)amino)-3-oxopropanoate (23).** To a suspension of compound 22 (0.844 g, 2.91 mmol) and potassium carbonate (804 mg, 5.81 mmol) in acetonitrile (20 mL) methyl malonyl chloride (343  $\mu$ L, 3.19 mmol) in acetonitrile (5 mL) was added dropwise and the reaction mixture was stirred at rt overnight. The solvent was evaporated and the solid residue was dissolved in ethyl acetate (20 mL). Organic phase was washed with water (2  $\times$  15 mL), saturated solution of NaHCO<sub>3</sub> (2  $\times$  15 mL) and brine (2  $\times$  15 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was evaporated under reduced pressure. The crude product was purified with flash column chromatography (ethyl acetate/petroleum ether = 1/2). Yield: 43%; white solid (550 mg); mp: 143 °C; R<sub>f</sub> (ethyl acetate/petroleum ether = 1/1): 0.29; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  1.47 (s, 9H, C(CH<sub>3</sub>)<sub>3</sub>), 2.71 (s, 3H, CH<sub>3</sub>), 3.49 (s, 2H, CH<sub>2</sub>), 3.67 (s, 3H, OCH<sub>3</sub>), 7.67 (dd, 1H, *J*<sub>1</sub> = 9.2 Hz, *J*<sub>2</sub> = 2.4 Hz, Ar-H-5), 8.06 (d, 1H, *J* = 8.8 Hz, Ar-H-6), 8.38 (d, 1H, *J* = 2.0 Hz, Ar-H-3), 9.26 (s, 1H, NH), 10.37 (s, 1H, NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  11.94 (CH<sub>3</sub>), 27.92 (C(CH<sub>3</sub>)<sub>3</sub>), 43.36 (CH<sub>2</sub>), 51.98 (OCH<sub>3</sub>), 78.96 (C(CH<sub>3</sub>)<sub>3</sub>), 115.02, 119.66, 120.95, 122.61, 133.21, 134.01, 152.29, 163.98, 166.80, 168.04, 176.66; IR (ATR)  $\nu$  = 3275, 3109, 2976, 2360, 2340, 1746, 1729, 1662, 1561, 1512, 1391, 1362, 1295, 1267, 1230, 1155, 1048, 1018, 766, 751 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 389.1 ([M-H]<sup>-</sup>), HRMS for C<sub>18</sub>H<sub>21</sub>N<sub>4</sub>O<sub>6</sub>: calculated 389.1461, found 389.1454.

**Methyl 3-((4-amino-3-(5-methyl-1,2,4-oxadiazol-3-yl)phenyl)amino)-3-oxopropanoate (24).** To a solution of compound 23 (50 mg, 0.13 mmol) in 1,4-dioxane (4 mL) 4 M HCl (320  $\mu$ L, 1.28 mmol) in 1,4-dioxane was added and the mixture was stirred overnight at rt. The solvent was evaporated under reduced pressure, to the solid residue ether (15 mL) was added, the obtained suspension was sonicated and the undissolved solid was filtered off, washed with ether and dried. Yield: 84%; grey solid (42 mg); mp: 122-123 °C; R<sub>f</sub> (dichloromethane/methanol/ammonia = 20/1/0.01): 0.61; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  2.69 (s, 3H, CH<sub>3</sub>), 3.48 (s, 2H, CH<sub>2</sub>), 3.57 (s, 3H, OCH<sub>3</sub>), 5.21 (s, 2H, NH<sub>2</sub>), 7.08 (d, 1H, *J* = 8.0 Hz, Ar-H-5), 7.53 (dd 1H, *J*<sub>1</sub> = 8.8 Hz, *J*<sub>2</sub> = 2.4 Hz, Ar-H-6), 8.28 (d, 1H, *J* = 2.4 Hz, Ar-H-2), 10.34 (s, 1H, NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>):  $\delta$  11.85 (CH<sub>3</sub>), 43.24 (CH<sub>2</sub>), 51.93 (OCH<sub>3</sub>), 110.66, 118.59, 120.04, 123.79, 130.70, 139.14, 163.60, 167.05, 168.20, 176.04; IR (ATR)  $\nu$  = 3531, 3469, 3226, 3051, 2847, 2580, 1727, 1717, 1582, 1553, 1508, 1362, 1346, 1264, 1131, 833, 717 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 291.1 ([M-H]<sup>+</sup>), HRMS for C<sub>13</sub>H<sub>15</sub>N<sub>4</sub>O<sub>4</sub>: calculated 291.1093, found 291.1092.

**Methyl 3-((4-(4,5-dibromo-1H-pyrrole-2-carboxamido)-3-(5-methyl-1,2,4-oxadiazol-3-yl)phenyl)amino)-3-oxopropanoate (25).** To a solution of 4,5-dibromopyrrol-2-carboxylic acid (1.30 mg, 1.01 mmol) in dichloromethane (7 mL) 2 M oxalyl chloride in dichloromethane (1.66 mL, 1.66 mmol) was added and the mixture was stirred overnight under an argon atmosphere. The solvent was evaporated, fresh dichloromethane (5 mL), pyridine (2.5 mL) and compound 23 (161 mg, 0.55 mmol) were added and the mixture was stirred at rt for 6 h. The solvent was evaporated and the solid residue was dissolved in ethyl acetate (15 mL). Organic phase was washed with water (2 × 10 mL), saturated solution of NaHCO<sub>3</sub> (2 × 10 mL) and brine (10 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and the solvent was removed under reduced pressure. Yield: 38%; white solid (176 mg); mp: 225-227 °C; R<sub>f</sub> (ethyl acetate/petroleum ether = 2/1): 0.21; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>): δ 2.72 (s, 3H, CH<sub>3</sub>), 3.51 (s, 2H, CH<sub>2</sub>), 3.68 (s, 3H, OCH<sub>3</sub>), 7.03 (s, 1H, pyrrol-CH), 7.72 (dd 1H, *J*<sub>1</sub> = 9.0 Hz, *J*<sub>2</sub> = 2.6 Hz, Ar-H-6), 8.16-8.19 (d, 1H, *J* = 8.8 Hz, Ar-H-5), 8.43 (d, 1H, *J* = 2.4 Hz, Ar-H-2), 10.28 (s, 1H, NH), 10.46 (s, 1H, NH), 13.07 (s, 1H, pyrrole-NH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>): δ 11.96 (CH<sub>3</sub>), 43.41 (CH<sub>2</sub>), 52.01 (OCH<sub>3</sub>), 98.44, 106.52, 113.29, 117.17, 119.60, 122.33, 123.60, 127.95, 132.25, 135.23, 157.02, 164.13, 166.73, 168.03, 176.83; IR (ATR)  $\nu$  = 3231, 3116, 2955, 2360, 1725, 1671, 1608, 1584, 1524, 1390, 1350, 1324, 1303, 1252, 1217, 1168, 808, 751, 636 cm<sup>-1</sup>; MS (ESI) *m/z* (%) = 537.9 ([M-H]<sup>-</sup>), HRMS for C<sub>18</sub>H<sub>14</sub>N<sub>5</sub>O<sub>5</sub>Br<sub>2</sub>: calculated 537.9362, found 537.9370; HPLC: t<sub>R</sub>: 12.046 min (95.4% at 280 nm).

#### 4. Conclusions

In the present study, we prepared two new series of *N*-phenyl-4,5-dibromopyrrolamides as potential inhibitors of GyrB. The most potent compound, **28**, had an IC<sub>50</sub> of 20 nM against DNA gyrase from *E. coli*. Additionally, compound **27**, an analogue of **28** that contains a 1,3,4-oxadiazole ring as the carboxylic group bioisostere had an IC<sub>50</sub> value of 40 nM. The structure-activity relationship data obtained suggest that for potent DNA gyrase inhibition, acidic or polar groups on R<sup>2</sup> or R<sup>3</sup> are crucial. Furthermore, this activity can be largely improved with the introduction of lipophilic groups to R<sup>1</sup>. The tested compounds did not show significant antibacterial activities, which is most likely due to their too low intracellular concentrations, either because of the problems with cell entry or because of the activity of efflux pumps. Since a positive correlation between the antibacterial activity of GyrB inhibitors and their pK<sub>a</sub> has been observed previously,<sup>11</sup> the penetration of compounds can possibly be improved by increasing the pK<sub>a</sub> of functionalities that

interact with Arg76 or Arg136, e.g. by introducing less acidic groups to positions R<sup>2</sup> or R<sup>3</sup>. Overall, in the design of new GyrB inhibitors, in addition to improving their on-target activities, the focus will have to be on optimising the size, shape and electronic properties of compounds to obtain their higher intracellular concentration and to avoid efflux.

## Conflicts of interest

There are no conflicts to declare.

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