

## Design, synthesis and molecular modeling study of substituted indoline-2-ones and spiro[indole-heterocycles] with potential activity against Gram-positive bacteria

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Longstanding and firsthand infectious diseases are challenging community health threats. A new series of isatin derivatives bearing  $\beta$ -hydroxy ketone, chalcone, or spiro-heterocycle moiety, was synthesized in a good yield. Chemical structures of the synthesized compounds were elucidated using spectroscopic techniques and elemental analysis. Antibacterial activities of the compounds were then evaluated *in vitro* and by *in silico* modeling. The compounds were more active against Gram-positive bacteria, *Staphylococcus aureus* (MIC = 0.026–0.226 mmol L<sup>-1</sup>) and *Bacillus subtilis* (MIC = 0.348–1.723 mmol L<sup>-1</sup>) than against Gram-negative bacteria (MIC = 0.817–7.393 mmol L<sup>-1</sup>). Only 3-hydroxy-3-(2-(2,5-dimethylthiophen-3-yl)-2-oxoethyl)indolin-2-one (**1b**) was found as active as imipenem against *S. aureus* (MIC = 0.026 mmol L<sup>-1</sup>). *In silico* docking of the compounds in the binding sites of a homology modeled structure of *S. aureus* histidine kinase-Walk allowed us to shed light on the binding mode of these novel inhibitors. The highest antibacterial activity of **1b** is consistent with its highest docking score values against *S. aureus* histidine kinase.

**Keywords:** 2-indolinone, spiro[indole-heterocycles], antimicrobial, docking study

Pathogenic infectious diseases pose a serious health problem. The mortality rate associated with infectious diseases is rapidly increasing due to a rapid increase in resistance of pathogenic strains (bacteria and fungi) against antimicrobials. This is prompting the search for novel antimicrobial agents to treat new infectious diseases and/or combat existing resistant microbes. Indole scaffold represents an interesting class of biologically active heterocyclic compounds. The scaffold possesses diverse biological activities including anti-inflammatory (1), anticonvulsant (2), antidepressant (3), antiallergic (4), antitubercular (5), antidiabetic (6), antiviral (7) and antimicrobial activity (8–11). Oxindole and other related ring systems also exhibit several biological activities (12–15). Thiosemicarbazone

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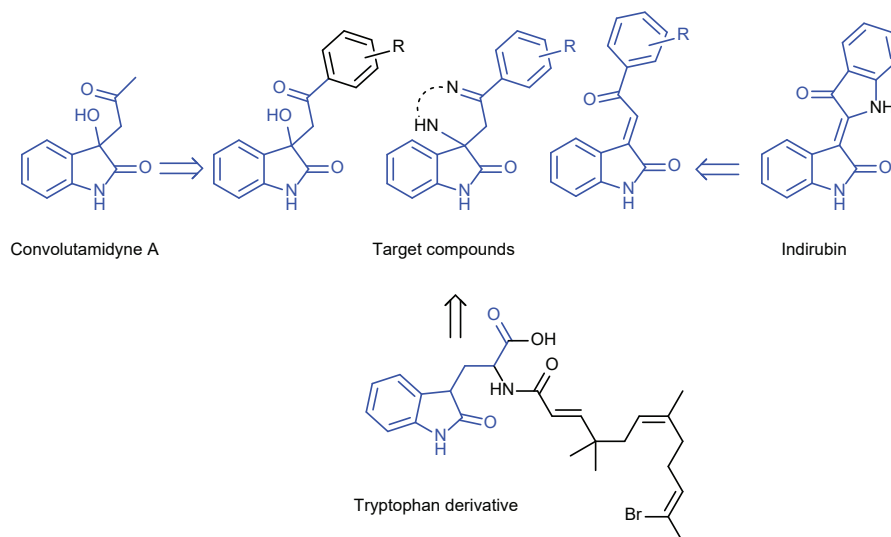


Fig. 1. Representative examples of bioactive heterocyclic molecules with oxindole moiety.

derivatives of indoline-2,3-dione show appreciable antifungal, antibacterial and antiviral activities *in vivo* and *in vitro* (16). New 1,3-dihydro-3-hydroxy-2H-indol-2-ones exhibit promising antibacterial and antifungal activities (17, 18). Benzylideneindolone derivatives have potent antimicrobial activity against *Staphylococcus aureus* at  $\mu\text{mol L}^{-1}$  concentrations (19).

Furthermore, 1H-indole-4,7-diones are potent inhibitors of *Candida krusei*, *Cryptococcus neoformans* and *Aspergillus niger* (20). Indirubin (Fig. 1) is prepared from natural plants (21) and is used in traditional Chinese medicine for the treatment of bacterial and viral infections (22). Further, convolutamidyne derivatives are representatives of bioactive 3-substituted-3-hydroxy-2-oxindole natural products (Fig. 1) with antioxidant activity (23). In addition, spiro-indoline-heterocycles have recently attracted much attention as important antimicrobials (24–26). Tryptophan-linked indole compound (Fig. 1) inhibits the enzymatic activity of histidine kinase (HK) enzyme in an *in vitro* assay ( $IC_{50} = 43.9 \text{ mmol L}^{-1}$ ); it also inhibits methicillin-resistant *S. aureus* (MRSA) and vancomycin-resistant *Enterococcus faecalis* ( $MIC = 100 \mu\text{g mL}^{-1}$  and  $50 \mu\text{g mL}^{-1}$ , resp.) (27).

Bacteria virulence is an adaptive response to extracellular changes through two-component system TCS pathways unique in bacteria (28). The *Staphylococcus aureus* bacteria TCS system comprises HK protein, containing WalK, a membrane-linked sensor protein, and a response regulator protein (RR) containing the DNA-binding domain (WalR) (29). WalK consists of two domains: one domain is a catalytic or ATP-binding domain and the second is a dimerization domain. When HK is activated by external stimuli, ATP binds at the catalytic domain of WalK, and the ATP phosphate group is transferred to a conserved histidine residue on the dimerization domain. Then, the phosphorylation of RR finally results in virulence as one of the bacterial responses to the extracellular stimulus (27). ATP-competitive inhibitors of the microbial HK/WalK are novel antibacterial agents (30, 31).

Given these findings and as a continuation of our work aimed to develop new potential antimicrobial compounds and other bioactive heterocycles based on the oxindole moiety (32–38), we synthesized novel derivatives including spiro[indole-heterocycles] in addition to the indolin-2-one scaffold bearing  $\beta$ -hydroxyl ketone group, chalcone moiety or spiro-heterocycle fragment. We were focused to generate a new lead structure with enhanced antimicrobial activity, possibly inhibiting the histidine kinase activities.

## EXPERIMENTAL

### Chemistry

Electrothermal IA9300 digital melting point apparatus (Cole-Parmer Ltd., UK) was used to determine the melting points of compounds in sealed tubes. Thin-layer chromatography was used to assess the purity of the compounds on aluminum TLC plates, silica gel coated with fluorescent indicator F254. Perkin Elmer FT-IR system, Spectrum BX (Perkin Elmer, USA) spectrophotometer was used to acquire the IR spectra using KBr-pellet technique, in a region of 4000–400  $\text{cm}^{-1}$ . Proton and  $^{13}\text{C}$  NMR spectra were recorded by using a 700 MHz spectrometer (Bruker Ascend<sup>TM</sup> 700, Bruker, USA) in  $\text{DMSO-}d_6$  as solvent and TMS as an internal standard. Chemical shifts are shown in  $\delta$  ppm. Mass spectra were obtained on Agilent 6410B Triple Quadrupole LC/MS spectrometer (Agilent Technologies, USA) using electron spray ionization at ESI 70 eV. Elemental analysis was performed on a 2400 CHNSO Perkin-Elmer analyzer. Chemicals and reagents, used in the study were purchased from Sigma-Aldrich Chemicals, USA).

### Syntheses

*General procedure for 3-hydroxy-3-(2-oxo-2-substituted ethyl)-indolin-2-ones (1a,b).* – A mixture of isatin (1.47 g, 0.01 mol), aryl/heteroaryl methyl ketone (0.01 mol) and diethylamine (1 mL) in ethanol (100 mL) was allowed to stand overnight at room temperature. The yellow needles which formed were recrystallized from ethanol.

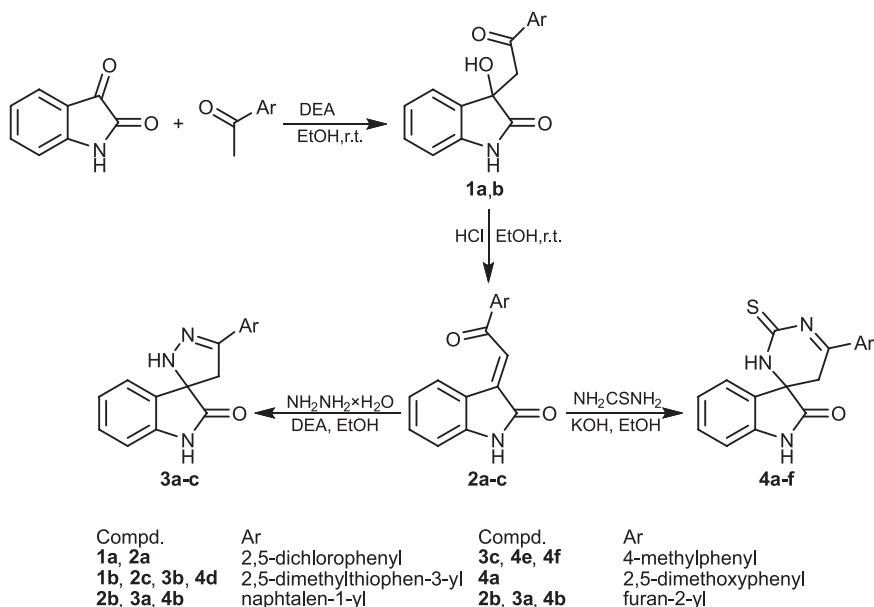
*General procedure for 3-(2-oxo-2-substituted ethylidene)indolin-2-ones (2a-c).* – To a mixture of 0.01 mol of compound **1a** or **1b** in 25 mL abs. ethanol, 50 mL of dilute HCl (25 %) was added. The reaction mixture was allowed to stand overnight and fine orange needles were formed.

*General procedure for spiro-indole-2-one-3,5'-(3-(substituted)-2-pyrazolines) (3a-c).* – To a mixture of 0.01 mol of respective compound **2** and hydrazine hydrate (50 %) in ethanol (20 mL), diethylamine (1 mL) was added. The reaction mixture was refluxed for 12–14 hours. Glacial acetic acid (10 mL) was added to the cold solution and the obtained precipitate was filtered, washed with ethanol and crystallized from glacial acetic acid.

*General procedure for spiro-indole-2-one-3,6'-(4-(substituted)-5,6-dihydropyrimidine-2-thiones) (4a-f).* – A mixture of a corresponding compound **2** (0.01 mol), thiourea (0.02 mol), potassium hydroxide (2 g), abs. ethyl alcohol (60 mL) and water (10 mL) was refluxed for 10–12 hours. The reaction mixture was concentrated, cooled and the formed precipitate was filtered, dried, and purified through recrystallization in absolute ethanol.

Table 1. Chemical names, molecular formula, elemental analyses, yields and melting points of compounds 1–4

Compd.	Chemical name	Molecular formula (M <sub>r</sub> )	Yield (%)	M. p. (°C)	CHNS analysis (%) calcd./found
<b>1a</b>	3-Hydroxy-3-(2-(2,5-dichlorophenyl)-2-oxoethyl)-indolin-2-one	C <sub>16</sub> H <sub>11</sub> Cl <sub>2</sub> NO <sub>3</sub> (335.01)	92	183–4	57.16 3.30 4.17 57.01 3.15 3.96
<b>1b</b>	3-Hydroxy-3-(2-(2,5-dimethylthiophen-3-yl)-2-oxoethyl)indolin-2-one	C <sub>16</sub> H <sub>15</sub> NO <sub>3</sub> S (301.08)	78	199–200	63.77 5.02 4.65 10.64 63.82 4.88 4.57 10.51
<b>2a</b>	3-(2-(2,5-Dichlorophenyl)-2-oxoethylidene)indolin-2-one	C <sub>16</sub> H <sub>9</sub> Cl <sub>2</sub> NO <sub>2</sub> (317)	80	222–223	60.40 2.85 4.40 60.55 2.71 4.32
<b>2b</b>	3-(2-(Naphthalen-1-yl)-2-oxoethylidene)indolin-2-one	C <sub>20</sub> H <sub>13</sub> NO <sub>2</sub> (299.09)	72	156–157	80.25 4.38 4.68 80.02 4.45 4.62
<b>2c</b>	3-(2-(2,5-Dimethylthiophen-3-yl)-2-oxoethylidene)indolin-2-one	C <sub>16</sub> H <sub>13</sub> NO <sub>2</sub> S (283.07)	78	222–223	67.82 4.62 4.94 11.32 68.01 4.54 4.82 11.15
<b>3a</b>	Spiro-indole-2-one-3,5'-(3-(naphthalen-1-yl)-2-pyrazoline)	C <sub>20</sub> H <sub>15</sub> N <sub>3</sub> O (313.12)	60	203–204	76.66 4.82 13.41 76.71 4.74 13.28
<b>3b</b>	Spiro-indole-2-one-3,5'-(3-(2,5-dimethylthiophen-3-yl)-2-pyrazoline)	C <sub>16</sub> H <sub>15</sub> N <sub>3</sub> O <sub>5</sub> (297.09)	54	182–183	64.62 5.08 14.13 64.53 5.15 14.21
<b>3c</b>	Spiro-indole-2-one-3,5'-(3-(4-methylphenyl)-2-pyrazoline)	C <sub>17</sub> H <sub>15</sub> N <sub>3</sub> O (277.12)	55	175–176	73.63 5.45 15.15 73.57 5.41 15.26
<b>4a</b>	Spiro-indole-2-one-3,6'-(4-(2,5-dimethoxyphenyl)-5,6-dihydropyrimidine-2-thione)	C <sub>18</sub> H <sub>15</sub> N <sub>3</sub> O <sub>2</sub> S (337.09)	65	163–164	64.08 4.48 12.45 9.50 63.95 4.42 12.33 9.62
<b>4b</b>	Spiro-indole-2-one-3,6'-(4-(naphthalene-1-yl)-5,6-dihydropyrimidine-2-thione)	C <sub>21</sub> H <sub>15</sub> N <sub>3</sub> O <sub>5</sub> (357.09)	60	178–179	70.57 4.23 11.76 8.97 70.41 4.17 11.62 8.86
<b>4c</b>	Spiro-indole-2-one-3,6'-(4-(furan-2-yl)-5,6-dihydropyrimidine-2-thione)	C <sub>15</sub> H <sub>11</sub> N <sub>3</sub> O <sub>2</sub> S (297.06)	52	165–166	60.59 3.73 14.13 10.78 60.51 3.65 13.94 10.69
<b>4d</b>	Spiro-indole-2-one-3,6'-(4-(2,5-dimethylthiophen-3-yl)-5,6-dihydropyrimidine-2-thione)	C <sub>17</sub> H <sub>15</sub> N <sub>3</sub> O <sub>5</sub> (341.07)	54	176–177	59.80 4.43 12.31 18.78 59.72 4.35 12.44 18.86
<b>4e</b>	Spiro-indole-2-one-3,6'-(4-(4-methylphenyl)-5,6-dihydropyrimidine-2-thione)	C <sub>18</sub> H <sub>15</sub> N <sub>3</sub> O <sub>5</sub> (321.09)	60	171–172	67.27 4.70 13.07 9.98 67.15 4.78 13.16 9.81
<b>4f</b>	Spiro-indole-2-one-3,6'-(4-(4-methoxyphenyl)-5,6-dihydropyrimidine-2-thione)	C <sub>18</sub> H <sub>15</sub> N <sub>3</sub> O <sub>2</sub> S (337.09)	56	158–159	64.08 4.48 12.45 9.50 64.01 4.35 12.31 9.42



Scheme 1.

Scheme 1 shows the pathway of the synthesis of the target compounds **1a,b** to **4a-f**. Their physicochemical data are given in Table I and their chemical structures were elucidated through FT-IR,  $^1\text{H}$  NMR,  $^{13}\text{C}$  NMR and mass spectral data and elemental analyses (Table II).

### In vitro antimicrobial screening

The activity of compounds (**1a,b** to **4a-f**) was evaluated against the Gram-positive bacteria *S. aureus* (ATCC 29213) and *B. subtilis* (ATCC 10400), Gram-negative bacteria *E. coli* (ATCC 35218) and *P. aeruginosa* (ATCC 27853) and fungal strain *C. albicans* (ATCC 2091) which were obtained from the American Type Culture Collection (ATCC, Manassas, VA, USA). Antimicrobial activity was assessed by serial twofold dilution method. Dimethyl sulfoxide (DMSO) was used as a negative control, imipenem was used as a standard drug for antibacterial activity testing and fluconazole was used as a standard drug for antifungal activity testing. All compounds were dissolved in DMSO at the concentration of 2048  $\mu\text{g mL}^{-1}$ . Two-fold dilutions of test and standard compounds were prepared in double strength nutrient broth (bacteria) or Sabouraud dextrose broth (fungi). The stock solutions were serially diluted to give concentrations between 2048 and 8  $\mu\text{g mL}^{-1}$  in the respective nutrient broth. The tubes were inoculated; inoculum size about  $10^6$  colony forming units (CFU)  $\text{mL}^{-1}$ . Then, the tubes were incubated at  $37 \pm 1$  °C for 24 h (bacteria) and at 25 °C for 7 days (fungi) and were macroscopically examined for turbidity. The culture tubes showing turbidity (lower concentration) and the culture tube showing no turbidity (higher concentration) gave the minimum inhibitory concentration (MIC) of the compound.

Table II. Spectral data of compounds **1a**, **b-4a-f**

Compd.	FTIR ( $\lambda_{max}$ , $\text{cm}^{-1}$ )	$^1\text{H NMR}$ (700 MHz, DMSO- $d_6$ , $\delta$ ppm)	$^{13}\text{C NMR}$ (100 MHz, DMSO- $d_6$ , $\delta$ ppm)	MS ( $m/z$ ): [M $^+$ ] calcd./found
	3456–3346 (O-H, N-H), 3150 (Ar-C-H), 2962 (Aliph-C-H), 1700 (C=O), 1623 (C=O)	3.51, 3.88 (1H, 1H, d, non-equivalent $\text{CH}_2$ ), 6.18 (1H, s, OH), 6.81–7.58 (ArH, m, 7H), 10.34 (1H, s, NH)	49.98 ( $\text{CH}_2$ ), 73.59 (indole C3), 110.02 (indole-CH), 121.78 (indole-CH), 124.61 (indole-CH), 128.82 (indole-CH), 129.26 (indole-CH), 129.70 (Ph-CH), 131.37 (Ph-CH), 132.42 (Ph-C), 132.53 (Ph-C), 132.59 (Ph-CH), 139.89 (Ph-C), 143.04 (indole-arC), 178.25 (C=O indole), 198.11 (C=O oxoethyl)	335.01 335.0
<b>1a</b>				
	3410–3363 (O-H, N-H), 3126 (Ar-C-H), 1708 (C=O), 1656 (C=O)	2.38 (3H, s, $\text{CH}_3$ ), 2.41 (2H, s, $\text{CH}_2$ ), 3.41 and 3.81 (2H, d, non-equivalent $\text{CH}_2$ ), 6.00 (1H, s, OH), 6.80–7.27 (ArH, m, 5H), 10.23 (1H, s, NH)	15.05 ( $\text{CH}_3$ ), 15.91 ( $\text{CH}_2$ ), 49.18 ( $\text{CH}_2$ ), 73.31 (indole-C3), 119.80 (indole-CH), 121.54 (indole-CH), 124.08 (indole-CH), 127.09 (indole-CH), 129.31 (indole-CH), 132.27 (thiophene-CH), 135.40 (thiophene-C), 135.57 (thiophene-C), 143.42 (indole-C), 146.59 (thiophene-C), 178.81 (indole-CO), 192.76 (oxoethyl-CO)	301.08 301.01
<b>1b</b>				
	3250 (NH), 3198 (Ar-CH), 1700 (C=O), 1623 (C=O)	6.81–7.86 (ArH, m, 7H), 8.28 (CO-CH=C<), 10.34 (1H, s, NH)	110.02 (indole-CH), 121.77 (indole-C), 124.60 (indole-CH), 127.98 (indole-CH), 128.81 (indole-CH), 129.69 (oxoethyl-C1), 130.04 (Ph-CH), 131.36 (Ph-CH), 132.42 (Ph-C), 132.53 (Ph-C), 132.58 (Ph-CH), 139.89 (Ph-C), 143.04 (indole-C), 146.09 (indole-C3), 178.25 (indole-CO), 198.11 (oxyethyl-CO)	317.00 316.89
<b>2a</b>				
	3211 (NH), 3063 (Ar-CH), 1705 (C=O), 1622 (C=O)	6.91–8.24 (ArH, m, 11H), 8.74 (CO-CH=C<, s, 1H), 10.86 (1H, s, NH)	110.89 (naph-CH), 120.46 (indole-CH), 122.25 (indole-C), 125.51 (indole-CH), 125.63 (indole-CH), 127.21 (indole-CH), 127.26 (naph-CH), 128.94 (naph-CH), 129.25 (naph-CH), 129.30 (naph-CH), 130.07 (naph-CH), 130.88 (naph-C), 134.04 (naph-CH), 134.41 (naph-CH), 134.96 (naph-C), 136.38 (indole-C), 145.45 (indole-C3), 168.77 (indol-CO), 194.67 (oxyethyl-CO)	299.09 299.02
<b>2b</b>				
	3221 (NH), 3190 (Ar-CH), 1707 (C=O), 1640 (C=O)	2.4 (3H, s, $\text{CH}_3$ ), 2.69 (3H, s, $\text{CH}_3$ ), 6.87–7.57 (ArH, m, 5H), 8.8 (CO-CH=C<), 10.77 (1H, s, NH)	14.96 ( $\text{CH}_3$ ), 16.25 ( $\text{CH}_3$ ), 110.75 (indole-CH), 120.48 (thiophene-C4), 122.30 (indole-CH), 126.85 (indole-CH), 127.26 (thiophene-CH), 128.76 (oxoethyl-C1), 133.18 (thiophene-C5), 135.8 (indole-CH), 136.24 (indole-CH), 136.88 (thiophene-C3), 145.18 (indole-C), 146.56 (indole-C3), 148.88 (thiophene-C2), 168.88, 186.86	283.07 283.01
<b>2c</b>				
	3361 (NH), 3138 (Ar-CH), 1681 (C=O)	3.57, 3.64 (2H, d, non-equivalent $\text{CH}_2$ ), 6.82–8.00 (11H, m, ArH), 10.56 (2H, s, NH)	46.61 (pyrazoline-C4), 56.51 (pyrazoline-C5), 110.21 (indole-CH), 121.65 (indole-CH), 122.72 (indole-CH), 124.85 (naph-CH), 125.82 (naph-CH), 126.08 (naph-CH), 126.42 (naph-CH), 127.35 (indole-CH), 127.59 (indole-CH), 127.78 (naph-C), 127.90 (indole-C), 133.99 (indole-C), 148.42 (pyrazoline-C3), 176.84 (indole-CO)	313.12 313.05
<b>3a</b>				

Compd.	FTIR ( $\lambda_{\text{max}}$ , $\text{cm}^{-1}$ )	$^1\text{H}$ NMR (700 MHz, DMSO- $d_6$ , $\delta$ ppm)	$^{13}\text{C}$ NMR (100 MHz, DMSO- $d_6$ , $\delta$ ppm)	MS ( $m/z$ ): [M] <sup>+</sup> calcd./found
<b>3b</b>	3356 (NH), 3154 (Ar-CH), 1680 (C=O)	2.36 (3H, s, CH <sub>3</sub> ), 2.52 (3H, s, CH <sub>3</sub> ), 3.29, 3.40 (2H, d, non-equivalent CH <sub>2</sub> ), 6.83–7.68 (5H, m, ArH), 10.36 (2H, s, two NH)	15.02 (CH <sub>3</sub> ), 15.04 (CH <sub>3</sub> ), 46.48 (pyrazoline-C4), 69.14 (pyrazoline-C5), 110.08 (indole-CH), 122.62 (indole-CH), 124.03 (indole-CH), 125.36 (indole-CH), 129.53 (thiophene-CH), 129.89 (thiophene-C), 131.98 (thiophene-C), 134.56 (thiophene-C), 135.22 (indole-C), 141.87 (indole-C), 145.63 (pyrazoline-C3), 178.79 (indole-CO)	297.09 297.01
<b>3c</b>	3295, 3150, 1680 (C=O)	2.32 (3H, s, CH <sub>3</sub> ), 3.29, 3.44 (non-equivalent 1H, 1H, s, CH <sub>2</sub> ), 6.85–8.45 (8H, m, ArH), 10.42 (1H, s, NH), 11.10 (1H, s, NH)	21.38 (CH <sub>3</sub> ), 44.25 (pyrazoline-C4), 69.58 (pyrazoline-C5), 110.13 (indole-CH), 121.64 (indole-CH), 122.71 (indole-CH), 124.26 (indole-CH), 126.19, 129.77 (Ph-CH), 132.81 (Ph-CH), 141.92 (indole-C), 147.92 (indole-C), 156.12 (pyrazoline-C3), 179.17 (indole-CO)	277.12 277.03
<b>4a</b>	3315 (NH), 1695 (CS), 1615 (CO)	3.38 (3H, s, CH <sub>3</sub> O), 3.50, 3.78 (1H, 1H, d, non-equivalent CH <sub>2</sub> ), 3.67 (3H, s, OCH <sub>3</sub> ), 6.67–7.17 (7H, m, ArH), 9.61 (2H, s, NH)	32.02 (pyrimidinethione-C5), 52.61 (CH <sub>3</sub> O), 55.57 (CH <sub>3</sub> O), 55.88 (pyrimidinethione-C6), 112.50 (Ph-CH), 114.55 (Ph-CH), 115.63 (Ph-CH), 116.32 (Ph-CH), 117.98 (indole-CH), 120.40 (indole-CH), 126.12 (indole-CH), 128.63 (indole-CH), 132.58 (indole-C), 134.25 (indole-C), 150.52 (Ph-C), 153.40 (Ph-C), 162.79 (pyrimidinethione-C4), 172.62 (C=O), 186.02 (C=5)	367.10 366.94
<b>4b</b>	3219 (NH), 1690 (CS), 1617 (CO)	3.66, 3.68 (1H, 1H, d, non-equivalent CH <sub>2</sub> ), 6.93–8.15 (11H, m, ArH), 9.34 (1H, s, NH), 10.85 (1H, s, NH)	30.52 (pyrimidinethione-C5), 52.43 (pyrimidinethione-C6), 124.01 (indole-CH), 125.30 (indole-CH), 125.95 (indole-CH), 126.85 (naph-CH), 127.43 (naph-CH), 128.38 (naph-CH), 128.74 (naph-CH), 128.98 (naph-CH), 129.70 (naph-CH), 130.09 (naph-CH), 130.87 (indole-CH), 133.30 (naph-C), 133.98 (naph-C), 135.33 (naph-C), 135.69 (indole-C), 154.29 (indole-C), 164.19 (pyrimidinethione-C4), 183.61 (CO), 202.22 (CS)	357.09 356.95
<b>4c</b>	3367 (NH), 1701 (CS), 1617 (CO)	3.61 (2H, s, CH <sub>2</sub> ), 6.43–7.92 (7H, m, ArH), 9.72 (1H, s, NH), 10.72 (1H, s, NH)	40.87 (pyrimidinethione-C5), 52.49 (pyrimidinethione-C6), 112.25 (furan-C3), 113.37 (furan-C4), 114.77 (indole-CH), 123.37 (indole-CH), 126.21 (indole-CH), 130.63 (indole-CH), 132.93 (indole-C), 137.94 (indole-C), 141.56 (furan-C2), 145.01 (furan-C5), 154.59 (pyrimidinethione-C3), 163.97 (CO), 183.90 (CS)	297.06 296.93
<b>4d</b>	3315 (NH), 1695 (CS), 1615 (CO)	2.42 (3H, s, CH <sub>3</sub> ), 2.58 (3H, s, CH <sub>3</sub> ), 3.37, 3.64 (1H, 1H, d, non-equivalent CH <sub>2</sub> ), 6.12–7.57 (5H, m, ArH), 9.43 (1H, s, two NH), 10.23 (1H, s, NH)	13.81 (CH <sub>3</sub> ), 15.96 (CH <sub>3</sub> ), 30.32 (pyrimidinethione-C5), 52.45 (pyrimidinethione-C6), 114.28 (thiophene-C4), 116.55 (thiophene-C3), 125.07 (indole-CH), 127.04 (indole-CH), 128.68 (indole-CH), 132.87 (indole-CH), 134.46 (thiophene-C5), 135.27 (thiophene-C2), 137.10 (indole-C), 146.02 (indole-C), 163.90 (pyrimidinethione-C3), 172.49 (CO), 185.27 (CS)	341.07 340.93

Compd.	FTIR ( $\lambda_{max}$ , $\text{cm}^{-1}$ )	$^1\text{H}$ NMR (700 MHz, DMSO- $d_6$ , $\delta$ ppm)	$^{13}\text{C}$ NMR (100 MHz, DMSO- $d_6$ , $\delta$ ppm)	MS ( $m/z$ ): [M] <sup>+</sup> calcd./found
<b>4e</b>	3447 (NH), 1700 (CS), 1654 (CO)	2.73 (3H, s, CH <sub>3</sub> ), 3.66, 3.68 (non-equivalent 1H, 1H, d, CH <sub>2</sub> ), 6.00–8.02 (8H, m, ArH), 10.10 (2H, s, two NH)	21.53 (CH <sub>3</sub> ), 30.52 (pyrimidinethione-C5), 52.44 (pyrimidinethione-C6), 125.17 (indole-CH), 125.35 (indole-CH), 125.53 (indole-CH), 126.96 (indole-CH), 128.36 (Ph-CH), 128.57 (Ph-CH), 129.04 (Ph-C), 130.08 (Ph-C), 133.33 (indole-C), 136.88 (indole-C), 164.17 (pyrimidinethione-C3), 172.51 (CO), 183.61 (CS)	321.09 320.89
<b>4f</b>	3400 (NH), 1724 (CS), 1618 (CO)	3.67 (3H, s, CH <sub>3</sub> O), 3.77, 3.87 (non-equivalent 1H, 1H, d, CH <sub>2</sub> ), 6.66–8.07 (8H, m, ArH), 9.57 (1H, s, NH), 10.79 (1H, s, NH)	40.88 (CH <sub>3</sub> O), 52.44 (pyrimidinethione-C5), 55.65 (pyrimidinethione-C6), 113.98 (Ph-CH), 124.37 (indole-CH), 130.67 (indole-CH), 130.76 (indole-CH), 131.42 (indole-CH), 131.64 (Ph-C), 132.28 (Ph-CH), 137.10 (indole-C), 137.60 (indole-C), 154.60 (Ph-C), 160.10 (pyrimidinethione-C3), 163.68 (CO), 183.55 (CS)	337.09 337.01

## Molecular modeling

**Homology modeling.** – The sequence of histidine kinase subunit A (Q7A2R7, 471 residues) (39) of *S. aureus* (strain Mu50/ATCC 700699) was used as a query for BLAST sequence-database search to identify similar X-ray structures (40). The structures were then ranked based on similarity percent. The top-ranked PDB entry was selected as a template for the alignment with Q7A2R7 and homology model building using the Modeller program (41). During modeling, the original position of the adenosine-5'-[beta,gamma-methylene]triphosphate (ACP ligand), as the X-ray ligand bound to the protein structure of the 5c93.pdb in the crystal structure, was retained to rebuild the binding cavity. The model of histidine kinase subunit A generated by homology modeling was used for the preparation of the input receptor files in the Dock6.4 program (42). The structures of the newly synthesized active compounds were used for flexible docking inside the binding site of the model using default dock6 parameters and Grid score including van der Waals and electrostatic target-ligand interaction of the ligand-binding conformation and the internal energy.

**Docking study.** – Molecular docking study was performed by using the Dock6.4 program on Ubuntu 14.2 (desktop Linux operating system) supported Dell 5000 Laptop, Processor, Intel(R) Core(TM) i7-5500U CPU @ 2.40GHz and system type 64-bit operating system, x64-based processor. Chemical structures of compounds **1a**, **b** to **4a-f** were generated in the protonated state under physiological conditions. The model of histidine kinase subunit A was used in the docking process without further minimization. Using the default settings of the program and defining a sphere of 10 Å diameter around the center of the binding pocket, the co-crystallized ligand was docked in the original protein structure. The resulting solutions were clustered based on the heavy atom root-mean-square deviation (RMSD) values (two superimposed atomic coordinates represent two different conformations only when RMSD > 1 Å). During docking, all torsion angles of the compound were set to free rotation and 10 binding poses per ligand were obtained. The binding pose with the highest total score was taken into consideration for ligand-receptor interactions.



## RESULTS AND DISCUSSION

### Chemistry

Scheme 1 shows the synthesis pathway of compounds **1a,b** to **4a-f**. Compounds 2,3-hydroxy-3-(2-oxo-2-substituted ethyl)-indolin-2-ones (**1a,b**) were obtained through the condensation of isatin with the appropriate acetophenone in the presence of diethylamine. In ethanolic HCl, compounds **1** underwent dehydration resulting in 3-(2-oxo-2-substituted ethylidene)indoline-2-ones (**2a-c**). The reaction of compounds **2a-c** with hydrazine hydrate led to hydrazone formation with subsequent intra-cyclization through nucleophilic Michael addition reaction resulting in spiro[indole-pyrazoline] compounds **3a-c**. The reaction of compounds **2a-c** with thiourea resulted in the formation of spiro[indole-dihydropyrimidine] compounds **4a-f**.

The compounds' structure was established based on IR, <sup>1</sup>H NMR, <sup>13</sup>C NMR and mass spectral, and elemental analysis data. IR spectra of **1a,b** revealed two characteristic bands at 1708–1700 cm<sup>-1</sup> and 1656–1623 cm<sup>-1</sup> (two C=O groups) and one band at 3456–3346 cm<sup>-1</sup> (OH). The latter band disappeared upon conversion of compounds **1a,b** into compounds **2a-c** which showed only two characteristic bands at 1707–1700 cm<sup>-1</sup> and 1640–1622 cm<sup>-1</sup> (two C=O groups). On the other hand, compounds **3a-c** showed characteristic bands at 1800 cm<sup>-1</sup> (one C=O group) while compounds **4a-f** showed characteristic bands at 1724–1695 cm<sup>-1</sup> (C=S group) and at 1654–1615 cm<sup>-1</sup> (one C=O group).

<sup>1</sup>H NMR spectra of compounds **1a,b** were characterized by the appearance of both OH signals at δ 5.83–6.18 ppm and non-equivalent methylene protons signals at δ 3.32–3.73 and δ 3.67–4.07 ppm. These signals disappeared, with the concomitant appearance of a singlet at δ 8.1–8.34 ppm associated with -CO-CH=C< moiety, in compounds **2a-c** confirming their formation. <sup>1</sup>H NMR spectra of compounds **3a-c** and **4a-f** were characterized by the appearance of non-equivalent methylene protons signals at δ 3.25–3.79 and δ 3.35–3.83 ppm, and at δ 3.37–3.66 and δ 3.64–3.78 ppm, resp. <sup>13</sup>C NMR spectra of compounds **1a,b** revealed characteristic signals at δ 49.8–49.18 ppm (CH<sub>2</sub> group), δ 73.59–73.31 ppm (indole-C3) and δ 198.11–192.76 ppm (oxoethyl-CO). Compounds **2a-c** showed characteristic signals at δ 146.56–145.45 ppm (indole-C3) and δ 198.11–186.86 ppm (oxoethyl-CO). On the other hand, <sup>13</sup>C NMR spectra of compounds **3a-c** showed characteristic signals at δ 46.61–44.25 (pyrazoline-C4) and at δ 69.58–56.51 (pyrazoline-C5) while compounds **4a-f** showed characteristic signals at δ 52.44–30.02 ppm (pyrimidinethione-C5) and at δ 55.88–52.43 (pyrimidinethione-C6).

Elemental analyses of the synthesized compounds **1a,b–4a-f** revealed that the mass percentage values found for carbon, hydrogen, nitrogen and sulfur were in accordance with the calculated values. The spiro compounds **3a-c** and **4a-f** showed higher nitrogen percentage values (> 11 %) than the compounds **1a,b** and **2a-c** (nitrogen percentage values > 5 %).

### Antimicrobial screening

Table III shows the results of antimicrobial screening of compounds **1a,b–4a-f**. The compounds showed weak antifungal activity, however, marked antibacterial activity was obtained. Compounds **1a,b** to **4a-f** showed promising activity against Gram-positive

Table III. Minimum inhibitory concentrations (MIC) of compounds **1a**, **b-4a-f**

Compd.	MIC (mmol L <sup>-1</sup> )					
	Gram-positive bacteria		Gram-negative bacteria		Fungus	
	<i>B. subtilis</i>	<i>S. aureus</i>	<i>E. coli</i>	<i>P. aeruginosa</i>	<i>C. albicans</i>	
<b>1a</b>	0.382	0.047	> 6.11	> 6.11	> 6.11	> 6.11
<b>1b</b>	0.425	0.026	0.85	1.7	3.4	3.4
<b>2a</b>	1.615	0.05	> 6.46	> 6.46	> 6.46	> 6.46
<b>2b</b>	0.856	0.107	6.849	> 6.849	> 6.849	> 6.849
<b>2c</b>	1.809	0.226	3.618	1.809	3.618	3.618
<b>3a</b>	0.817	0.102	0.817	1.635	3.271	3.271
<b>3b</b>	0.43	0.053	1.723	> 6.895	> 6.895	> 6.895
<b>3c</b>	0.924	0.057	3.696	> 7.393	> 7.393	> 7.393
<b>4a</b>	0.348	0.087	1.395	> 5.58	> 5.58	> 5.58
<b>4b</b>	1.434	0.044	2.868	> 5.736	> 5.736	> 5.736
<b>4c</b>	1.723	0.053	1.723	> 6.895	> 6.895	> 6.895
<b>4d</b>	0.75	0.046	1.501	> 6.005	> 6.005	> 6.005
<b>4e</b>	0.797	0.049	3.19	> 6.38	> 6.38	> 6.38
<b>4f</b>	0.379	0.047	3.038	> 6.077	> 6.077	> 6.077
Imipenem	0.026	0.026	0.026	0.026	0.026	–
Fluconazole	–	–	–	–	–	0.0008

bacteria with the higher activity against *S. aureus* ( $MIC = 0.026\text{--}0.226 \text{ mmol L}^{-1}$ ) than *B. subtilis* ( $MIC = 0.348\text{--}1.723 \text{ mmol L}^{-1}$ ) and fair activity against Gram-negative bacteria ( $MIC = 0.817\text{--}7.393 \text{ mmol L}^{-1}$ ). As far as *S. aureus* is concerned compounds **1a,b** ( $MIC = 0.026\text{--}0.047 \text{ mmol L}^{-1}$ ) are more active than compounds **2a-c** ( $MIC = 0.05\text{--}0.226 \text{ mmol L}^{-1}$ ) and **3a-c** and **4a-f** ( $MIC 0.044\text{--}0.102 \text{ mmol L}^{-1}$ ).

Acid-catalysed dehydration of  $\beta$ -hydroxy ketone, compound **1a** ( $MIC, S. aureus, 0.047 \text{ mmol L}^{-1}$ ) resulted in almost as active chalcone compound **2a** ( $MIC, S. aureus, 0.05 \text{ mmol L}^{-1}$ ). Moreover,  $\beta$ -hydroxy ketone **1b** was found equipotent with the reference drug imipenem ( $MIC, S. aureus, 0.026 \text{ mmol L}^{-1}$ ), however, transforming it into chalcone type candidate produced a nine-fold less potent compound **2c** ( $MIC, S. aureus, 0.226 \text{ mmol L}^{-1}$ ). Transformation of the chalcone **2b** ( $MIC, S. aureus 0.107 \text{ mmol L}^{-1}$ ) into spiro[indole-pyrazoline] led to compound **3a** with comparable antibacterial activity ( $MIC, S. aureus 0.102 \text{ mmol L}^{-1}$ ), however, its cyclization into spiro[indole-dihydropyrimidinethione] produced compound **4b** with 2.5-fold enhanced potency ( $MIC, S. aureus 0.044 \text{ mmol L}^{-1}$ ). Cyclization of the least active compound **2c** produced active spiro[indole-pyrazoline] **3b** ( $MIC, S. aureus 0.053 \text{ mmol L}^{-1}$ ), and spiro[indole-dihydropyrimidinethione] **4d** ( $MIC, S. aureus 0.046 \text{ mmol L}^{-1}$ ).

### Molecular modeling study

The 3D structure of *S. aureus* histidine kinase is unavailable. Therefore, to investigate the possible interactions between compounds **1a,b** to **4a-f** and the amino acids that form the binding site of *S. aureus* histidine kinase, homology modeling of the sequence entry Q7A2R7 with subsequent docking process were performed. Using the BLAST alignment protocol, the crystal structure of a monomer histidine kinase domain complex with ACP (5c93.A) of *E. coli* (43), was chosen as a template. The choice was based on BLAST-p alignment and top pairwise percentage residue identity (36.53 %) and similarity (38 %). During homology modeling, after the heavy atoms have been modeled and all hydrogen atoms added, the protein coordinates were minimized using the AMBER94 force field. Briefly, the structure is a compact single domain with 5-stranded  $\beta$ -sheet and 7- $\alpha$ -helices and random coils (Fig. 2). The



Fig 2. The backbone structure of *S. aureus* histidine kinase (Q7A2R7) (homolog model, colored cyan) overlaid onto that of 5c93A.pdb (template structure, colored grey).

Table IV. Results of docking study of compounds **1a**, **b-4a-f**

Compd.	Amino acid(s) of the receptor involved in the H-bond	H-bond distance (Å)	Grid score energy (kcal mol <sup>-1</sup> )	Es energy (kcal mol <sup>-1</sup> )	VDW energy (kcal mol <sup>-1</sup> )
<b>1a</b>	Gly 418 Leu 421	2.293 2.093	-34.250	-1.030	-33.220
<b>1b</b>	Gly 418	2.148	-36.231	-0.697	-35.534
<b>2a</b>	Gly 420	2.439	-30.423	-0.407	-30.016
<b>2b</b>	Gly 418	2.569	-30.165	0.686	-30.851
<b>2c</b>	Tyr 362 Lys 361	2.369 2.361	-33.296	0.413	-33.709
<b>3a</b>	Leu 421	2.125	-31.692	0.313	-32.005
<b>3b</b>	Leu 421	1.809	-31.698	0.524	-32.222
<b>3c</b>	Asn 358	1.975	-29.757	-0.026	-29.731
<b>4a</b>	Asn 358 Leu 419	2.286 2.477	-22.402	0.242	-22.644
<b>4b</b>	Asn 417	2.079	-23.424	1.551	-24.975
<b>4c</b>	Asn 358 Asn 417	2.364 1.746	-19.967	-1.588	-18.379
<b>4d</b>	Lys 361	1.825	-23.323	-1.006	-22.327
<b>4e</b>	Lys 361 Asn 358	2.051 2.162	-20.883	-1.422	-22.305
<b>4f</b>	Lys 361	2.247	-23.597	-0.578	-23.019

Es – electrostatic energy, VDW energy – van der Waals energy

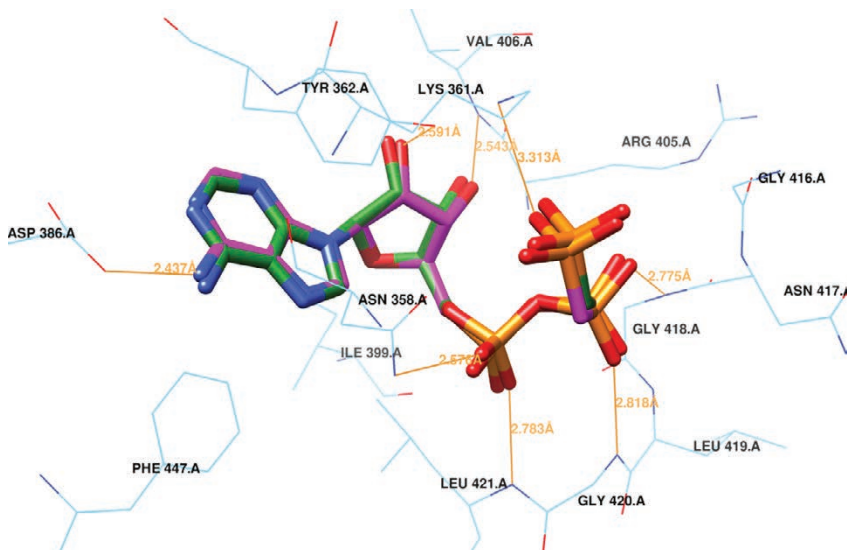


Fig. 3. The co-crystallized ACP (from 5c93.pdb, colored magenta) and the re-docked ACP structure (colored forest green), superimposed inside the binding site of homology-modeled Q7A2R7.

RMSD value of the pose from the redocking of the ACP structure itself (0.704 Å) confirmed the appropriateness of the docking approach (Fig. 3). The binding site includes a hydrophobic pocket delineated with the side-chains of Asp 358, Lys 361, Tyr 362, Asp 386, Ile 399, Arg 405, Val 406, Gly 416, Asn 417, Gly 418, Leu 419, Gly 420, and Leu 421.

The docking poses of the newly synthesized compounds **1a,b** to **4a-f** showed hydrogen bonding between the C-3 hydroxyl group of the isatin moiety, the C-2 carbonyl oxygen of the isatin moiety, the carbonyl oxygen of the acetophenone moiety and the NH group of the binding site residues Asn 417, Asn 418, Gly 420, Asn 358, Tyr 360 or Asn 461 (Fig. 4 and Table IV). The derived docking scores for compounds **1a,b** to **4a-f** were in agreement with

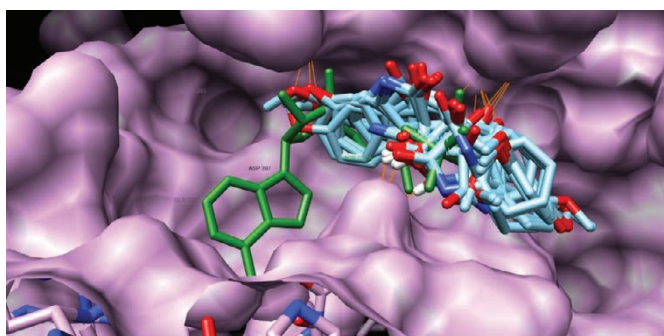


Fig. 4. The newly synthesized compounds (colored cyan) overlaid the X-ray ligand ACP (colored forest green) inside the binding site, hydrogen bonds are displayed in orange color).

the obtained MICs against *S. aureus* and also with the notion that the antibacterial effects of indoline-2-one derivatives might be associated with the inhibition of the histidine kinase-mediated pathway (44). 3-Hydroxy-3-(2-(2,5-dimethylthiophen-3-yl)-2-oxoethyl)indolin-2-one (compound **1b**) was found most active against *S. aureus* (MIC = 0.026 mmol L<sup>-1</sup>) and also showed the top-score in the docking study (grid score in energy -36.231 kcal mol<sup>-1</sup>) (Tables III and Table IV).

## CONCLUSIONS

In summary, a series of new isatin compounds bearing either  $\beta$ -hydroxyketone or chalcone moieties were synthesized and biologically evaluated for their antimicrobial activity. The compounds showed promising activity against Gram-positive bacteria with the highest specific activity against *S. aureus*. 3-Hydroxy-3-(2-(2,5-dimethylthiophen-3-yl)-2-oxoethyl)indolin-2-one (**1b**) was the most active against *S. aureus* (MIC 0.026 mmol L<sup>-1</sup>) equivalent to the value exerted by imipenem, whereas compounds **1a**, **2a**, **3b,c** and **4b-f** showed comparable activity (MIC = 0.044–0.057 mmol L<sup>-1</sup>). The highest activity of **1b** against *S. aureus* is consistent with its highest docking score values inside the binding site of *S. aureus* histidine kinase (grid score -36.231 kcal mol<sup>-1</sup>, electrostatic energy -0.697 kcal mol<sup>-1</sup>, and van der Waals energy -35.534 kcal mol<sup>-1</sup>). The main contribution to the docking grid score is from van der Waals energy that reflects high geometric complementarity which is well known essential for the specific binding.

Analysis of the binding mode of compounds **1a,b** to **4a-f** to a modeled-structure of histidine kinase revealed that these compounds had the same orientation in the binding site, and the same hydrogen bonding as well as the X-ray ligand ACP. The high activity of compounds **1a,b** are supposed to be attributed to the free rotation of the isatin scaffold around the bond between indole-C3 and methylene group of the oxyethyl substituent. This flexibility plays role in binding efficiency with the histidine kinase receptor. The higher activity and top-ranked docking score of compound **1b** suggest it as a lead compound for further optimization to design and synthesize more potent and selective anti-*S. aureus* compounds.

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Supplementary material is available upon request.

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