Design, Synthesis, and Antidepressant Activity Study of Novel Aryl Piperazines Targeting Both 5-HT_{1A} and Sigma-1 Receptors

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Abstract

A total of 20 novel aryl piperazine derivatives were designed and synthesized, and their structures were confirmed by mass spectrometry and nuclear magnetic resonance analyses. Their 5-HT_{1A} and sigma-1 receptor affinities were determined, and six of them showed high affinities ($K_i < 20$ nmol/L) to both 5-HT_{1A} and sigma-1 targets. Then, metabolic stability ($T_{1/2}$) tests of six compounds in rat and human liver microsomes were performed. Our data indicated that compound 27 has both high affinity for 5-HT_{1A} and sigma-1 receptors ($5-HT_{1A}: K_i = 0.44$ nmol/L; sigma-1: $K_i = 0.27$ nmol/L), and good metabolic stability ($T_{1/2}$ values are 21.7 and 24.6 minutes, respectively). Interestingly, results from the forced swimming test, mouse tail suspension test, and preliminary pharmacokinetic test suggested the marked antidepressant activity, good pharmacokinetic characteristics, and low toxicity of compound 27 in the two models. In conclusion, compound 27 has great value of further study as an active molecule of antidepressant drugs.
**Introduction**

Depression, the third biggest health problem in the world, is estimated to become the second biggest health burden in the world by 2030. Depression therapy is mainly focused on antidepressants in clinics, which are often associated with slow effect and severe side effects, such as sexual dysfunction, nausea, insomnia, or weight gain, as well as loss of cognitive ability. The choice of treatment for depression is still limited. Therefore, it is very important to develop new antidepressants with rapid onset, low side effects, and improved cognitive function. Among which the research and development of new dual- or multi-target antidepressants is an important direction in the field.

Serotonin (5-hydroxytryptamine, 5-HT) is a neurotransmitter distributed in the central and peripheral nervous systems. 5-HT1A receptor (5-HT1AR) is the first isolated and fully sequenced subtype of the 5-HT receptor family, and is widely considered as a target for the treatment of anxiety, depression, schizophrenia, and neurodegenerative diseases such as Parkinson’s disease and Alzheimer’s disease. 5-HT1AR partial agonist vilazodone (5-HT1A, Ki = 1.50 nM/L) is a good antidepressant drug that has been successfully marketed (Fig. 1).

Sigma-1 (σ1) receptor is a nonopioid receptor and widely distributed in the central nervous system. σ1 receptor plays an important role in regulating a variety of neural activities. Several small molecules with good affinity for σ1 receptor have been applied to the pathological study of pain, depression, schizophrenia, etc. Evidence suggested that Jo-1784 (σ1, Ki = 75 nM/L) delivered “antidepressant-like” effects in animal behavioral models of depression in forced swimming test (FST), tail suspension test (TST), and clinical trials (Fig. 1). Fluvoxamine, usually considered as a serotonin reuptake inhibitor actually, has high affinity for σ1 receptor, and it is believed that its clinical effect of improving cognition and alleviating anxiety is mainly attributed to σ1 receptor agonism.

Early studies by Skuza and Rogóz showed that in the FST of rats, the combined use of 5-HT1A and σ1 receptor agonists could dose-dependently reduce the interaction of immobility duration. Otsuka Pharmaceutical company developed the antidepressant OPC (OPC-14523), which exhibits high in vitro affinities for 5-HT1AR, σ1 receptor, and serotonin transporter (Fig. 1). Compared with other selective serotonin reuptake inhibitors, OPC-14523 has significantly shorter onset time and significantly improved cognitive ability. Therefore, exploring the compounds acting on both 5-HT1A and σ1 receptors as new potential antidepressant active molecules has scientific basis and feasibility.

Research studies have revealed that N-alkylated tetrahydroisoquinoline (TIQ) derivatives could produce slight affinity differences for the binding of subtypes of 5-HT receptor family, with medium to good selectivity. Besides, arylpiperazine derivatives, especially compounds with long carbon chains connected to the N atom of dichlorophenylpiperazines, can be used clinically to treat central nervous system diseases, such as listed drugs aripiprazole, brilaroxazine, and cariprazine (Fig. 2).

Inspired by the above research, arylalkyl piperazine derivatives obtained by carbon chain fusion of TIQ and its electronic, isosteric, and arylpiperazine parts may have the synergistic effect to target 5-HT1A and σ1 receptors at the same time. Herein, we designed four classes of dual-target agonist, TIQ phenylpiperazine derivatives (class A compounds), thiopehene tetrahydropyridine phenylpiperazine derivatives (class B compounds), dihydroindole phenylpiperazine derivatives (class C compounds), and benzonitrogen seven-membered heterocyclic phenylpiperazine derivatives (class D compounds) as shown in Fig. 3. All the four classes of compounds are subject to the affinity test of 5-HT1A and σ1 receptors. Compounds with a high affinity of 5-HT1A and σ1 receptors are further examined for their in vitro liver microsomal stability test, yielding optimal compounds. On this basis, the antidepressant and preliminary pharmacokinetic (PK) studies of the optimal compounds are performed to find...
the bioactive and druggable compounds. At the same time, the structure–activity relationship analysis is performed to guide the discovery of better antidepressant compounds targeting 5-HT1A and σ1 receptors.

Results and Discussion

Structure, In Vitro Activity, and Synthesis of the Compounds

Through replacing 3,4-dihydroquinolinone of the lead compound OPC-14523 with 1,2,3,4-tetrahydroisoquinolines, class A compounds 11–18 were obtained. Table 1 lists the derivatives’ structures and target binding affinities. Our data indicated that the compounds obtained by replacing 3,4-dihydroquinolinone of OPC-14523 with TIQ derivatives have high affinity for 5-HT1A and σ1 receptors, such as compounds 17 and 18.

To explore influences of different nitrogen-containing aromatic heterocycles on the affinity of 5-HT1A and σ1 receptors, the electronic isosteres of TIQ were designed. By replacing TIQ in the above-mentioned type A compounds with tetrahydropyridine, dihydroindole, and benzoazepine seven-membered heterocyclic ring, 12 compounds (19–30) of type B, C, and D were prepared. Their structures and target binding affinities are determined and shown in Table 2. The results exhibited that compounds 19, 20, and 27 had high affinity for the two targets, suggesting that the substitution of thiophene tetrahydropyridine and (R)-8-chloro-1-methyl-2,3,4,5-tetrahydro-1H-benzo [D] azo group for TIQ could obtain a highly active dual-target action compound.

The above compounds (11–30) were synthesized by a two-step synthesis route (Scheme 1). Briefly, the substituted phenylpiperazines (commercially available) were reacted with 1-bromo-2-chloroethane or 1-bromo-3-chloropropane in the presence of potassium carbonate to obtain intermediates 5–10, which were condensed with different substituted aromatic nitrogen-containing heterocycles under the action of potassium carbonate and potassium iodide to obtain target compounds 11–30, respectively.

Preliminary Structure–Activity Relationship Analysis

Results from the preliminary structure–activity relationship analysis showed that:

- When the length of carbon chain between TIQ and phenylpiperazine is 2, the affinity of compounds for two targets was significantly better than three-carbon compounds, such as compound 15 (4.0 nmol/L, 11.1 nmol/L) > compound 11 (484.1 nmol/L, 59.4 nmol/L), compound 16 > compound 12.
- When there were substitutions on the TIQ ring, the affinity activity for two targets was significantly better than that of unsubstituted compounds on the ring, such as compounds 17 and 18 > compound 15.
- The affinity of phenylpiperazine compounds with two chlorine substituents to σ1 receptor was significantly higher than that with two methyl substituents, such as compound 15 > 16.
- When TIQ of A compounds was replaced by a tetrahydrothiophenopyridine ring, their affinity for two targets was significantly improved, such as compounds 19 and 20 > compound 15.
- Compounds containing dihydroindole with CN at C-3 have a strong affinity for 5-HT1A but a weak affinity for σ1 receptor, such as compounds 22 and 24. If CN was substituted at C-4, the affinity for both receptors was lost, such as compounds 21 and 23.
- Among the benzodiazepine seven-membered heterocyclic compounds, the activity of methyl compound 27 with R configuration to both targets (0.44 and 0.27 nmol/L) was significantly better than compound 28 with S configuration.

In Vitro Liver Microsomal Stability Test

Compounds 15, 17, 18, 19, 20, and 27 with good affinities (K_i < 20 nmol/L) for 5-HT1A and σ1 receptors were selected for liver microsomal stability test. The results showed that compound 27 had a long half-life and good metabolic stability in human and rat liver microsomes (HLM and RLM) with HLM T_1/2 and RLM T_1/2 being 24.6 and 21.7 minutes, respectively, as shown in Table 3.

In vivo Pharmacokinetic Test of Compound 27

In vivo PK evaluation of compound 27 was performed in rats. Our data showed that intravenous administration of 27 (5 mg/kg) produced detectable plasma levels of the compound with a half-life (T_1/2) of 18.39 hours. Besides, the T_1/2 values of the oral administration of the compound for 30 and 100 mg/kg doses were 24.07 and 39.49 hours, respectively, and the bioavailability values were 5.90 and 10.40%, suggesting that compound 27 had good PK characteristics (Table 4).
Study on the Antidepressant-Like Activity of Compound 27

Forced Swim Test
ICR (Institute of Cancer Research) male mice were randomly divided into five groups, and then intragastrically administered with different doses of compound 27 (10, 30, and 90 mg/kg) and positive drug duloxetine (20 mg/kg/d) for 7 consecutive days. Our data indicated that 27 dose-dependently decreased the immobility time by 12, 23, and 58% when compared with the negative control. The antidepressant-like effect of 27 was statistically significant at a high dose (90 mg/kg), as shown in Fig. 4.

Mouse Tail Suspension Test
Compound 27 was intragastrically administered at 10, 30, and 90 mg/kg/d (po) for 7 consecutive days to three of five groups of randomly assigned ICR male mice, and duloxetine

| Compd. | Structure | 5-HT$_{1A}$ ($K_i$, nmol/L) | Sigma-1 ($K_i$, nmol/L) |
|-------|-----------|-----------------------------|------------------------|
| 11    | ![Structure](image1) | 484.1 | 59.4 |
| 12    | ![Structure](image2) | 244.9 | 863.9 |
| 13    | ![Structure](image3) | 0.7 | 278 |
| 14    | ![Structure](image4) | >1,000 | 0.33 |
| 15    | ![Structure](image5) | 4 | 11.1 |
| 16    | ![Structure](image6) | 3.9 | 158.6 |
| 17    | ![Structure](image7) | 2.3 | 3.5 |
| 18    | ![Structure](image8) | 3 | 0.46 |
| Compd. | Structure | $5$-HT$_{1A}$ ($K_i$, nmol/L) | Sigma-1 ($K_i$, nmol/L) |
|-------|-----------|----------------------------|------------------------|
| 19    | ![Structure 19](image1) | 0.18                      | 0.08                   |
| 20    | ![Structure 20](image2) | 0.21                      | 0.08                   |
| 21    | ![Structure 21](image3) | $>1,000$                  | $>1,000$               |
| 22    | ![Structure 22](image4) | 2.3                       | $>1,000$               |
| 23    | ![Structure 23](image5) | $>1,000$                  | $>1,000$               |
| 24    | ![Structure 24](image6) | 43.4                      | 608                    |
| 25    | ![Structure 25](image7) | $>1,000$                  | 1.1                    |
| 26    | ![Structure 26](image8) | 519.8                     | 2.0                    |
| 27    | ![Structure 27](image9) | 0.44                      | 0.27                   |
| 28    | ![Structure 28](image10) | $>1,000$                  | 1.55                   |
| 29    | ![Structure 29](image11) | 289.6                     | 9.7                    |
| 30    | ![Structure 30](image12) | 660.2                     | 112.0                  |
served as the positive control (20 mg/kg/d, po). Results from the TST showed that in comparison to the excipient group, the immobility time of compound 27 was apparently reduced by 17, 20, and 70%, and the reduction of immobility time was statistically significant at the dose of 90 mg/kg. The results are shown in ▶Fig. 5.

**Acute Toxicity Test of Compound 27**

The experimental method of single gavage in mice was used. The results showed that the LD50 and maximum tolerable dose (MTD) of compound 27 were 1,600 and 1,000 mg/kg, respectively, and the MTD of the positive control drug vortioxetine was 300 mg/kg, indicating that the acute toxicity of compound 27 was low and well tolerated.

**Conclusion**

OPC-14523 was used as the lead compound. In this study, the 3,4-dihydroquinolinone of OPC-14523 was replaced by 1,2,3,4-tetrahydroisoquinoline to obtain class A compounds, then nitrogen-containing aromatic heterocycles were substituted for the TIQ structure of class A compounds to give a total of 20 new arylalkyl piperazine compounds (compounds 11–30). The affinity test of 5-HT1A and σ1 receptor indicated that compounds 15, 17, 19, 20, and 27 had high affinities (Ki < 20 nmol/L) for the two targets; next the stability (T1/2) tests of the six compounds in RLM and HLM were performed. The results revealed that compound 27

**Table 3** Metabolic stability study in liver microsomes

| Compd. | RLM T1/2 (min) | HLM T1/2 (min) |
|--------|----------------|----------------|
| 15     | 1.7            | 8.7            |
| 17     | 2.6            | 7.2            |
| 18     | 1.6            | 5.0            |
| 19     | 1.9            | 1.7            |
| 20     | 3.5            | 21.6           |
| 27     | 21.7           | 24.6           |

Abbreviations: HLM, human liver microsome; RLM, rat liver microsome.

**Table 4** PK profiles of compound 27 in rats

| Dose (mg/kg) | Cmax (ng/mL) | Tmax (h) | CL (L/h/kg) | T1/2 (h) | AUC0-t (ug/L × h) | AUC0-inf (ug/L × h) | F (%) |
|--------------|--------------|----------|-------------|----------|------------------|---------------------|------|
| 5 (iv)       | 501          | 0.08     | 2.79        | 18.39    | 1,254            | 1900                | 5.90 |
| 30 (po)      | 116          | 0.83     | 33.79       | 24.07    | 438              | 901                 | 5.90 |
| 100 (po)     | 115          | 2.83     | 25.76       | 39.49    | 1,305            | 5141                | 10.40|

Abbreviation: PK, pharmacokinetics.
showed high affinity for 5-HT<sub>1A</sub> and α1 receptors (5-HT<sub>1A</sub>:<br>K<sub>i</sub> = 0.44 nmol/L; α1: K<sub>i</sub> = 0.27 nmol/L) and had good metabolic stability (t<sub>1/2</sub> values are 21.7 and 24.6 minutes, respectively). FST, TST, and preliminary PK test of compound 27 showed that 27 exhibited good antidepressant activity in both models, and had good PK characteristics and low acute toxicity. Compound 27 is a promising active molecule of antidepressants. Our study provides a useful reference for the design and synthesis of new multi-target antidepressant compounds with higher activity, lower side effects, and good druggability.

**Experimental Section**

**General Synthetic Procedure of 11–18**
The substituted phenylpiperazine (10 mmol), 1-bromo-3-chloropropane (20 mmol), and potassium carbonate (24 mmol) were dissolved in 80 mL acetone. The mixture was stirred at 60°C for 8 hours. The reaction mixture was rotary-evaporated to remove acetone, added dichloromethane (80 mL) and water (80 mL) for extraction. The organic phase was separated, dried with anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated to obtain the crude product, which was purified by column chromatography (petroleum ether:ethyl acetate = 5:1) to give a white solid (5).

1-(3-Chloropropyl)-4-(2,3-dimethylphenyl)piperazine (compound 5, 4.8 mmol), TIQ (4.8 mmol), potassium carbonate (14.4 mmol), and potassium iodide (4.8 mmol) were dissolved in 50 mL of acetonitrile. The mixture was stirred at 82°C for 7 hours. After the completion of the reaction, the solution was distilled off under reduced pressure. The residue was diluted with 50 mL of water and 30 mL of dichloromethane for extraction. The organic phase was separated, dried with anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated to obtain a residue, which was purified by column chromatography to give a white solid.

The above solid was dissolved in 30 mL ethyl acetate, then 2 mol/L hydrogen chloride–ethyl acetate solution was slowly added to adjust the pH to the desired value (pH 2–3). During the addition, a solid was precipitated, filtered, and then dried under vacuum to give the target product (11; white solid; yield: 18.3%).

2-(3-(4-(2,3-Dichlorophenyl)piperazin-1-yl)propyl)-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (11): white solid; yield: 18.3%. ESI-MS (m/z): calcd. for C<sub>24</sub>H<sub>32</sub>Cl<sub>2</sub>N<sub>3</sub>O<sub>2</sub>·HCl<sup>+</sup> [M + H]<sup>+</sup> 404.1565; found 404.1. <sup>1</sup>H NMR (400 MHz, DMSO) δ 11.56 (s, 1H), 11.33 (s, 1H), 7.42–7.34 (m, 2H), 7.30–7.19 (m, 5H), 4.60 (d, J = 15.6 Hz, 1H), 4.31 (dd, J = 15.6, 7.6 Hz, 1H), 3.78–3.60 (m, 3H), 3.49–3.41 (m, 2H), 3.37–3.20 (m, 10H), 3.04 (m, 1H), 2.45–2.32 (m, 2H).

2-(3-(4-(2,3-Dimethylphenyl)piperazin-1-yl)propyl)-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (12): white solid; yield: 85%. ESI-MS (m/z): calcd. for C<sub>22</sub>H<sub>28</sub>Cl<sub>4</sub>N<sub>3</sub>·HCl<sup>+</sup> [M + H]<sup>+</sup> 364.2747; found 364.2. <sup>1</sup>H NMR (400 MHz, DMSO) δ 11.36 (s, 2H), 7.32–7.18 (m, 4H), 7.09 (t, J = 8.0 Hz, 1H), 6.94 (d, J = 8.4 Hz, 1H), 6.91 (d, J = 8.4 Hz, 1H), 4.60 (d, J = 14.8 Hz, 1H), 4.31 (dd, J = 15.4, 8.0 Hz, 1H), 3.90–3.70 (m, 8H), 3.68–3.50 (m, 2H), 3.41–3.32 (m, 4H), 3.28–3.01 (m, 2H), 2.45–2.30 (m, 2H), 2.23 (s, 3H), 2.18 (s, 3H).

6,7-Dichloro-2-(3-(4-(2,3-dichlorophenyl)piperazin-1-yl)propyl)-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (13): white solid; yield: 25.1%. ESI-MS (m/z): calcd. for C<sub>24</sub>H<sub>26</sub>Cl<sub>4</sub>N<sub>3</sub>·HCl<sup>+</sup> [M + H]<sup>+</sup> 472.0875; found 472.2. <sup>1</sup>H NMR (400 MHz, DMSO) δ 11.32 (s, 1H), 11.30 (s,1H), 7.62 (s, 1H), 7.56 (s, 1H), 7.59 (dd, J = 7.6, 2.0 Hz, 1H), 7.37 (t, J = 8.0 Hz, 1H), 7.23 (dd, J = 7.6, 2.0 Hz, 1H), 4.60 (d, J = 14.8 Hz, 1H), 4.41–4.29 (m, 1H), 3.80–3.69 (m, 1H), 3.68–3.55 (m, 2H), 3.54–3.39 (m, 6H), 3.37–3.12 (m, 6H), 3.11–3.01 (m, 1H), 2.42–2.25 (m, 2H).

2-(3-(4-(2,3-Dichlorophenyl)piperazin-1-yl)propyl)-6,7-dimethoxy-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (14): white solid; yield: 34%. ESI-MS (m/z): calcd. for C<sub>21</sub>H<sub>29</sub>Cl<sub>2</sub>N<sub>3</sub>O<sub>2</sub>·HCl<sup>+</sup> [M + H]<sup>+</sup> 464.1866; found 464.3. <sup>1</sup>H NMR (400 MHz, DMSO) δ 11.13 (s, 1H), 10.74 (s, 1H), 7.43–7.33 (m, 2H), 7.26–7.20 (m, 1H), 6.84 (s, 1H), 6.78 (s, 1H), 4.48 (d, J = 15.2 Hz, 1H), 4.20 (dd, J = 15.3, 7.3 Hz, 1H), 3.75 (s, 3H), 3.74 (s, 3H), 3.69 (m, 1H), 3.63 (d, J = 8.3 Hz, 2H), 3.47 (d, J = 9.5 Hz, 2H), 3.35–3.25 (m, 4H), 3.24 (d, J = 9.0 Hz, 6H), 2.95 (d, J = 16.8 Hz, 1H), 2.32 (m, 2H).

2-(2-(4-(2,3-Dichlorophenyl)piperazin-1-yl)ethyl)-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (15): white solid; yield: 11.6%. ESI-MS (m/z): calcd. for C<sub>21</sub>H<sub>29</sub>Cl<sub>2</sub>N<sub>3</sub>·HCl<sup>+</sup> [M + H]<sup>+</sup> 390.1498; found 390.1. <sup>1</sup>H NMR (400 MHz, DMSO) δ 11.35 (s, 1H), 11.33 (s, 1H), 7.45–7.33 (m, 2H), 7.39–7.23 (m, 1H), 6.93 (s, 1H), 6.79 (s, 1H), 4.44 (d, J = 15.2 Hz, 1H), 4.20 (dd, J = 15.3, 7.3 Hz, 1H), 3.78 (d, 3H), 3.74 (s, 3H), 3.72 (m, 1H), 3.62 (d, J = 8.3 Hz, 2H), 3.48 (d, J = 9.5 Hz, 2H), 3.34–3.25 (m, 4H), 3.23 (d, J = 9.0 Hz, 6H), 2.95 (d, J = 16.8 Hz, 1H), 2.32 (m, 2H).
(400 MHz, DMSO) δ 10.89 (s, 2H), 7.34–7.27 (m, 2H), 7.22 (d, J = 5.9 Hz, 2H), 7.15 (dd, J = 12.8, 6.8 Hz, 1H), 6.98 (dd, J = 13.5, 7.7 Hz, 2H), 3.93–3.65 (m, 4H), 3.38 (m, 10H), 3.2 (d, J = 23.6 Hz, 4H).

2-(4-(2,3-Dimethylphenyl)piperazin-1-yl)ethyl)-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (16): white solid; yield: 27%. ESI-MS (m/z): calcd. for C_{22}H_{27}N_{5}^{+} [M + H]^+ 350.2591; found 350.2. 1H NMR (400 MHz, DMSO) δ 11.06 (s, 2H), 7.29 (d, J = 6.3 Hz, 2H), 7.20 (d, J = 5.9 Hz, 2H), 7.08 (t, J = 7.7 Hz, 1H), 6.93 (dd, J = 13.5, 7.7 Hz, 2H), 4.80–4.60 (m, 1H), 4.49–4.25 (m, 1H), 3.95–3.65 (m, 6H), 3.40–3.30 (m, 10H), 2.23 (s, 3H), 2.19 (s, 3H).

6,7-Dichloro-2-(4-(2,3-dichlorophenyl)piperazin-1-yl)ethyl)-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (17): white solid; yield: 48.3%. ESI-MS (m/z): calcd. for C_{21}H_{24}Cl_{2}N_{3}^{+} [M + H]^+ 458.0719; found 458.1. 1H NMR (400 MHz, DMSO) δ 11.19 (s, 2H), 7.62 (s, 1H), 7.51 (s, 1H), 7.39 (dd, J = 8.0, 2.0 Hz, 1H), 7.36 (t, J = 8.4 Hz, 1H), 7.23 (dd, J = 7.6, 2.0 Hz, 1H), 4.70–4.56 (m, 1H), 4.45–4.24 (m, 1H), 4.05–2.96 (m, 16H).

2-(4-(2,3-Dichlorophenyl)piperazin-1-yl)ethyl-1-methyl-1,2,3,4-tetrahydroisoquinoline dihydrochloride salt (18): white solid; yield: 50%. ESI-MS (m/z): calcd. for C_{22}H_{26}Cl_{2}N_{4}^{+} [M + H]^+ 404.1655; found 404.2. 1H NMR (400 MHz, DMSO) δ 11.54–11.16 (m, 2H), 7.42–7.33 (m, 2H), 7.33–7.20 (m, 5H), 4.82 (m, 1H), 3.82–3.51 (m, 10H), 3.34–3.25 (m, 6H), 3.07 (d, J = 17.6 Hz, 1H), 2.09–1.56 (m, 2H).

**General Synthetic Procedure for 19–20**

The substituted phenylpiperazine (10 mmol), 1-bromo-2-chloroethane (20 mmol), and potassium carbonate (24 mmol) were dissolved in acetone (80 mL). The mixture was stirred at 60°C for 8 hours. The reaction mixture was rotary-evaporated to remove acetone, and diluted with dichloromethane (80 mL) and water (80 mL) for extraction. The organic phase was separated, dried with anhydrous Na2SO4, and concentrated to obtain the crude product, which was purified by column chromatography (petroleum ether:ethyl acetate = 5:1) to give a white solid (19).

1-(2-Chloroethyl)-4-(2,3-dichlorophenyl)piperazine (compound 8, 5 mmol), indoline-5-carbonitrile (5 mmol), potassium carbonate (15 mmol), and potassium iodide (5 mmol) were dissolved in acetonitrile (60 mL), and the mixture was stirred at 82°C for 7 hours. The solvent was distilled off under reduced pressure. After the completion of the reaction, the solvent was distilled off under reduced pressure. The residue was diluted with water (50 mL) and dichloromethane (40 mL) for extraction. The organic phase was separated, dried with anhydrous Na2SO4, and concentrated to obtain a residue, which was purified by column chromatography (petroleum ether:ethyl acetate = 3:1) to give a light yellow oily liquid.

The above light yellow oily liquid was dissolved in 30 mL ethyl acetate, then 2 mol/L hydrogen chloride–ethyl acetate solution was slowly added to adjust the pH to the desired value (pH 2–3). Solid was precipitated, filtered, and then dried in a vacuum to give the target product (19: white solid; yield: 74%).

5-(2-(4-(2,3-Dichlorophenyl)piperazin-1-yl)ethyl)-4,5,6,7-tetrahydrothieno[3,2-c]pyridine dihydrochloride salt (19): white solid; yield: 74%. ESI-MS (m/z): calcd. for C_{19}H_{24}Cl_{2}N_{3}S^{+} [M + H]^+ 396.1063; found 396.1. 1H NMR (400 MHz, DMSO) δ 11.14 (s, 1H), 10.94 (s, 1H), 7.33–7.27 (m, 2H), 7.25 (d, J = 5.1 Hz, 1H), 7.14 (dd, J = 6.6, 3.0 Hz, 1H), 6.78 (d, J = 5.1 Hz, 1H), 3.52–3.50 (m, 2H), 3.00–2.95 (m, 4H), 2.78–2.74 (m, 4H), 2.67–2.53 (m, 8H).

2-Chloro-5-(2-(4-(2,3-dichlorophenyl)piperazin-1-yl)ethyl)-4,5,6,7-tetrahydrothieno[3,2-c]pyridine dihydrochloride salt (20): white solid; yield: 14%. ESI-MS (m/z): calcd. for C_{19}H_{24}Cl_{2}N_{3}S^{+} [M + H]^+ 430.0673; found 430.0. 1H NMR (400 MHz, DMSO) δ 11.29 (s, 2H), 7.33–7.26 (m, 2H), 7.14 (dd, J = 6.6, 3.1 Hz, 1H), 6.81 (s, 1H), 3.49–3.40 (m, 2H), 2.99–2.95 (m, 4H), 2.75 (dd, J = 7.0, 4.7 Hz, 2H), 2.72–2.68 (m, 2H), 2.65–2.52 (m, 8H).

**General Synthetic Procedure for 21–24**

The substituted phenylpiperazine (10 mmol), 1-bromo-2-chloroethane (20 mmol), and potassium carbonate (24 mmol) were dissolved in acetone (80 mL). The mixture was stirred at 60°C for 8 hours. The resulting mixture was rotary-evaporated to remove acetone, and diluted with dichloromethane (80 mL) and water (80 mL) for extraction. The organic phase was separated, dried with anhydrous Na2SO4, and then concentrated to obtain the crude product, which was purified by column chromatography (petroleum ether:ethyl acetate = 5:1) to give a white solid (8).

1-(2-Chloroethyl)-4-(2,3-dichlorophenyl)piperazine (compound 8, 5 mmol), indoline-5-carbonitrile (5 mmol), potassium carbonate (15 mmol), and potassium iodide (5 mmol) were dissolved in acetonitrile (60 mL), and the mixture was stirred at 82°C for 7 hours. The solvent was distilled off under reduced pressure. And then 50 mL of water and 40 mL of dichloromethane were added for extraction. The organic phase was separated, dried with anhydrous Na2SO4, and concentrated to give a residue.

The residue was dissolved in 30 mL ethyl acetate, and then 2 mol/L hydrogen chloride–ethyl acetate solution was slowly added to adjust to pH to the desired value (pH 2–3). During the addition, solids are precipitated, filtered, recrystallized using ethanol to obtain the target product (21: white solid; yield: 30%).

1-(2-Chloroethyl)-4-(2,3-dichlorophenyl)piperazine (4-5 mol), indoline-5-carbonitrile (5 mol), potassium carbonate (15 mol), and potassium iodide (5 mol) were dissolved in acetonitrile (60 mL), and the mixture was stirred at 82°C for 7 hours. After the completion of the reaction, the solvent was distilled off under reduced pressure. The residue was diluted with water (50 mL) and dichloromethane (40 mL) for extraction. The organic phase was separated, dried with anhydrous Na2SO4, and concentrated to obtain a residue, which was purified by column chromatography (petroleum ether:ethyl acetate = 3:1) to give a light yellow oily liquid.

The above light yellow oily liquid was dissolved in 30 mL ethyl acetate, then 2 mol/L hydrogen chloride–ethyl acetate solution was slowly added to adjust the pH to the desired value (pH 2–3). Solid is precipitated, filtered, and then dried in vacuum to give the target product (19: white solid; yield: 74%).
1-(3-(4-(2,3-Dichlorophenyl)piperazin-1-yl)propyl)indoline-5-carboxitrihydrochloride salt (23): white solid; yield: 34.7%. ESI-MS (m/z): calcd. for C_{22}H_{25}Cl_{3}N_{3} \cdot [M + H]^+ 415.1451; found 415.1. \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) δ 13.09 (s, 1H), 7.39 (d, J = 8.0 Hz, 1H), 7.32–7.24 (m, 2H), 7.21 (t, J = 8.0 Hz, 1H), 7.03 (d, J = 6.7 Hz, 1H), 6.47 (d, J = 8.3 Hz, 1H), 3.80–3.50 (m, 6H), 3.48–3.25 (m, 4H), 3.08 (t, J = 8.5 Hz, 6H), 2.40 (s, 2H).

1-(3-(4-(2,3-Dichlorophenyl)piperazin-1-yl)propyl)indoline-4-carboxitrihydrochloride salt (24): white solid; yield: 37.6%. ESI-MS (m/z): calcd. for C_{22}H_{25}Cl_{3}N_{3} \cdot [M + H]^+ 415.1451; found 415.2. \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) δ 13.03 (s, 1H), 7.51 (d, J = 7.6 Hz, 1H), 7.20 (dd, J = 13.6, 9.6 Hz, 2H), 7.01 (dd, J = 13.9, 7.8 Hz, 2H), 6.75 (d, J = 8.1 Hz, 1H), 3.67 (t, J = 12.0 Hz, 4H), 3.59 (t, J = 8.2 Hz, 2H), 3.47–3.28 (m, 4H), 3.22 (t, J = 8.0 Hz, 2H), 3.10 (t, J = 6.5 Hz, 2H), 2.97 (t, J = 7.4 Hz, 2H), 2.40 (t, J = 7.5 Hz, 2H).

General Synthetic Procedure for 25–30

The substituted phenylpiperazine (10 mmol), 1-bromo-2-chloroethane (20 mmol), and potassium carbonate (24 mmol) were dissolved in 80 mL acetone. The mixture was stirred at 60°C for 8 hours. The resulting mixture was rotary-evaporated to remove acetone. The residue was diluted with dichloromethane (80 mL) and water (80 mL) for extraction. The organic phase was separated, dried with anhydrous Na_2SO_4, and concentrated to obtain the crude product, which was purified by column chromatography (petroleum ether: ethyl acetate = 5:1) to give a white solid (8).

1-(2-Chloroethyl)-4-(2,3-dichlorophenyl)piperazine (compound 8, 5.1 mmol) and (R)-8-chloro-1-methyl-2,3,4,5-tetrahydro-1H-benzo[d]azepine (5.1 mmol), potassium carbonate (15.4 mmol), and potassium iodide (5.1 mmol) were dissolved in 60 mL acetonitrile. The mixture was stirred at 82°C for 7 hours. The solvent was distilled off under reduced pressure. The residue was diluted with 50 mL of water and 40 mL of dichloromethane for extraction. The organic phase was separated, dried with anhydrous Na_2SO_4, and purified with column chromatography (petroleum ether:ethyl acetate = 20:1 - 3:1) to give an oily liquid.

The above oily liquid was dissolved in 30 mL ethyl acetate, and 2 mol/L hydrogen chloride–ethyl acetate solution was slowly added to adjust the pH to the desired value (pH 2–3). During the addition, solids were precipitated, which were filtered and dried under vacuum to obtain the target product (25) white solid; yield: 82.0%.

(R)-8-Chloro-3-(2-(4-(2,3-dichlorophenyl)piperazin-1-yl)ethyl)-1-methyl-2,3,4,5-tetrahydro-1H-benzo[d]azepine dihydrochloride salt (26): white solid; yield: 79.3%. ESI-MS (m/z): calcd. for C_{23}H_{28}Cl_{3}N_{3} \cdot [M + H]^+ 452.1422; found 452.3. \textsuperscript{1}H NMR (400 MHz, DMSO) δ 11.32 (s, 1H), 10.65 (s, 1H), 7.31–7.22 (m, 2H), 7.15–7.04 (m, 4H), 3.05 (t, J = 7.3 Hz, 1H), 2.97–2.74 (m, 6H), 2.70–2.30 (m, 12H), 1.23 (d, J = 7.2 Hz, 3H).

Receptor Binding Assay

The binding affinity for 5-HT\textsubscript{1A}R was performed by incubating the displacement of \textsuperscript{3}H]-8-OH-DPAT to HEK-293 cell membrane homogenates at 37°C for 10 minutes, in Tris/HCl buffer (50 mmol/L, pH 7.7). The \textsuperscript{3}H receptor binding assay was determined by Jurkat cell membranes with \textsuperscript{3}H]-(-)-pentazocine at 37°C for 2 hours, in 5 mmol/L Tris/HCl buffer (pH 7.4). The \textsuperscript{3}H values for 5-HT\textsubscript{1A} and \textsuperscript{3}H were calculated from the corresponding IC\textsubscript{50} values according to the method of Cheng–Prusoff. The binding affinity results were expressed as means of at least three separate experiments.
Method for Studying the Stability of Liver Microsomes

To a solution of 20 μL 10 μmol/L standard working solution (substrate reaction concentration: 1 μmol/L) was added 140 μL 5.7 mmol/L cold MgCl₂ solution. After well mixing, RLM and HLM proteins (cold; 20 μL 5 g/L; reaction concentration: 0.5 g/L) were supplemented. The solution was preincubated at 37°C in a water bath for 5 minutes, then added 20 μL 10 mmol/L NADPH (reaction concentration: 1.0 mmol/L) for the same preincubation for 5 minutes. The reaction was conducted in a 37°C water bath for 0, 5, 10, 20, 30, and 60 minutes, and terminated with 400 μL ice methanol. The resulting solution was vortexed for 3 minutes, and centrifuged at 12,000 rpm at 4°C for 10 minutes. The concentration of the target compounds in the supernatant was detected at each incubation time point using the established liquid chromatography–mass spectrometry (LC-MS) method. The mobile phase was acetonitrile–10 mmol/L ammonium acetate with 0.02% formic acid being added. By comparing with the concentration of the 0 hour sample, the metabolic rates of the target compounds were measured after incubation with RLM and HLM.

Chromatographic conditions of six compounds are as follows: the chromatographic column is Agilent extended C18 column (150 mm × 4.6 mm, 5 μm, Agilent, United States); the precolumn is C18 protective column (4 mm × 3.0 mm, 5 μm, Phenomenex, United States); the flow rate is 1.0 mL/min; the column temperature is 30°C. Mass spectrometric conditions: the ionization mode is electrospray ionization; the temperature is 350°C; selective ion monitoring, positive ion detection; the dryer temperature is 350°C; the fragmentation voltage is 70 V; the atomizer pressure (psi) is 35; the dry air velocity is 8 L/min; and the high vacuum is 1.3E-005Torr.

In Vivo Pharmacokinetic Test

Eighty healthy male Sprague-Dawley rats were randomly divided into three groups. Rats in the three groups were given 27 by tail vein (5.0 mg/kg), gavage (30 mg/kg), and gavage (100 mg/kg), respectively. After administration, rat blood was collected from orbit at different time points. Drug concentration in the plasma was measured by LC-MS. The PK parameters and absolute bioavailability were calculated by DAS2.0 software.

For the detail, the methods can be described as follows: (1) intravenous administration group: six Sprague-Dawley male rats were fasted for 12 hours with water access freely prior to drug dosing. The rats were given 27 solution (1.0 mg/mL in glucose injection) by tail vein injection at the dose of 5.0 mg/kg. Then 0.3 mL blood was collected from fundus venous plexus before and after drug administration at 5, 15, 30, and 60 minutes, as well as 2, 4, 7, 10, and 24 hours, respectively, and centrifuged at 4,000 rpm for 10 minutes. The plasma was stored at –20°C in a refrigerator for further study. (2) Intragastric administration group: six Sprague-Dawley male rats were fasted for 12 hours with water access freely prior to drug dosing. The rats were given 3 and 10 mg/mL 27 solution by gavage at the dose of 30 and 100 mg/kg. Then 0.3 mL blood was collected from fundus venous plexus before and after drug administration at 10, 20, 30, and 60 minutes, and 2, 4, 7, 10, and 24 hours, respectively, and then centrifuged at 4,000 rpm for 10 minutes. The plasma was stored at –20°C in a refrigerator for further study.

FST Assay

ICR male mice were randomly divided into five groups. Compound 27 were intragastrically administered at doses of 10, 30, and 90 mg/kg and duloxetine (20 mg/kg/d) for 7 consecutive days. The drug was administered 1 hour before each experiment. In the test, the mice were placed in a water pool (15 cm depth with water temperature of 23–25°C) in a transparent glass cylinder for 6 minutes, and at the same time, videotaped for 6 minutes. Then the immobility time of mice during swimming was recorded and analyzed.

TST Assay

ICR male mice were given vehicle, duloxetine (control drug, 20 mg/kg/d, po) as well as 27 (10, 30, and 90 mg/kg, po) for 7 consecutive days. The drug was administered 1 hour before each experiment. In the TST, the mice were pasted with adhesive tape 1 cm away from its tail tip, and hung for 6 minutes for video recording. Then, the immobility time of mice during the tail suspension period was analyzed.

Ethics Statement

The present study was approved by the animal ethics committee and abides by the relevant agreements of the Jiangsu Enhua Pharmaceutical Co., Ltd., Jiangsu, People’s Republic of China.

Conflict of Interest

None.

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