Design and discovery of a high affinity, selective and β-arrestin biased 5-HT7 receptor agonist

Edem K. Onyameh1 · Edward Ofori1,4 · Barbara A. Bricker1 · Uma M. Gonela1 · Suresh V. K. Eyunni1 · Hye J. Kang2,3 · Chandrashekar Voshavar1 · Seth Y. Ablordeppey1

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Abstract

Compound 1c, 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-2,3-dihydro-1H-inden-1-one was previously reported from our laboratory showing high affinity binding to the 5-HT7 receptor (Ki = 0.5 nM). However, compound 1c racemizes readily upon enantiomeric separation. To prevent racemization, we have redesigned and synthesized methyl and carboxyethyl analogs, compounds 2 and 3 respectively, whose binding affinities were similar to those of compound 1c. Compounds 2 and 3 cannot undergo racemization since tautomerism was no longer possible and thus, compound 2 was selected for enantiomeric separation and further evaluation. Upon enantiomeric separation, the levorotatory enantiomer, (−)-2 or 2a demonstrated a higher affinity (Ki = 1.2 nM) than the (+)-2 or 2b enantiomer (Ki = 93 nM) and a β-arrestin biased functional selectivity for the 5-HT7 receptor. Although 2a showed about 8 times less activity than 5-HT in the Gs pathway, it showed over 31 times higher activity than 5-HT in the β-arrestin pathway. This constitutes a significant β-arrestin pathway preference and shows 2a to be more potent and more efficacious than the recently published β-arrestin biased 3-(4-chlorophenyl)-1,4,5,6,7,8-hexahydropyrazolo[3,4-d]azepine, the N-debenzylated analog of JNJ18038683 (Compound 7).

Graphical Abstract

Keywords 5-HT7 receptor · Indanone · Tetrahydroisoquinoline · β-arrestin-biased ligand · 5-HT7R agonist · Eutomer

Abbreviations

5-HT Serotonin
5-HT7R Serotonin-7 receptor
CNS Central Nervous System
DA Dopamine
DAT Dopamine transporter
D2R Dopamine D2 Receptor
DMEM Dulbecco’s Modified Eagle Medium
cAMP Cyclic adenosine monophosphate
EC50 Half maximal effective concentration
Emax Maximal efficacy
HPLC High performance liquid chromatography
IFD Induced Fit Docking

1 Division of Basic Pharmaceutical Sciences, College of Pharmacy and Pharmaceutical Sciences, Florida A&M University, Tallahassee, FL 32307, USA
2 Department of Pharmacology, School of Medicine, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-7365, USA
3 National Institute of Mental Health Psychoactive Drug Screening Program (NIMH PDSP), School of Medicine, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-7365, USA
4 Present address: College of Pharmacy, Chicago State University, 9501 S. King Dr., Douglas Hall, Chicago, Il 60626, USA

* Seth Y. Ablordeppey
seth.ablordeppey@famu.edu

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Introduction

The serotonin-7 receptor (5-HT\(_7\)-R), the newest discovery of the 5-HTRs, is discretely localized in the thalamus, hypothalamus, cortical and limbic regions of the Central Nervous System (CNS) as well as in the periphery [1, 2]. The pharmacology and therapeutic potential of the 5-HT\(_7\) receptor and its involvement in several pathophysiological conditions have recently been reviewed [3]. Furthermore, several lines of evidence have implicated the role of 5-HT\(_7\)-R in neuropsychiatric diseases including depression, pain, migraine, schizophrenia, and disorders related to circadian rhythm [4, 5]. Studies have also shown that blockade or inactivation of the 5-HT\(_7\)-R has led to antidepressant-like behavior [6]. These observations have led to the hypothesis that the 5-HT\(_7\)-R could serve as a new target for the design of drugs for the treatment of depression and other CNS diseases [7].

SB-269970, JNJ18038683, and SB-258719 are 5-HT\(_7\)-R antagonists (Fig. 1) that have served as primary tools for the pharmacological characterization of the 5-HT\(_7\)-R [8, 9]. In addition, the selective 5-HT\(_7\)-R agonists AS-19 [10], E-55888, LP-12, LP-44, and Compound 7 (Fig. 1) have been used to characterize the involvement of the 5-HT\(_7\)-R in CNS conditions including memory and cognition [11]. More recently, it has been suggested that 5-HT\(_7\)-R agonists may be useful in the treatment of alcohol and drug abuse [12]. Furthermore, there have been efforts to identify new agents that not only show selectivity for the 5-HT\(_7\)-R, but also display signaling bias to allow for further characterization of the 5-HT\(_7\)-R [13, 18]. In a previous study, we reported a campaign to identify new, high affinity 5-HT\(_7\)-R ligands that might find utility in treating some of the cognitive symptoms of schizophrenia and especially identifying new ligands that display a bias for the signaling pathways at the 5-HT\(_7\)-R [14, 19]. This was in response to recent research indicating noncanonical modes of G protein-coupled receptor (GPCR) signaling through \(\beta\)-arrestins, which trigger specific signaling pathways that are independent of G protein activation [15]. In addition, there have been discovery of ligands that block G protein activation but promoted \(\beta\)-arrestin binding, or vice-versa, suggesting the possibility of selectively activating intracellular signaling pathways [15]. Biased agonism is a relatively new concept which postulates that certain GPCRs can activate complex signaling networks to adopt multiple active conformations upon agonist binding [16], and in fact, biased agonists selectively stabilize only a subset of receptor conformations induced by a ligand. This thus, suggest the possibility that one can direct cellular signaling with precision and specificity and further support the notion that biased agonists may produce new classes of therapeutic agents that have fewer side effects [17]. Indeed, a 5-HT\(_7\)-R targeting \(\beta\)-arrestin biased ligand was reported to modulate NREM (non-rapid eye movement) and REM (rapid eye movement) sleep times indicating the potential of 5-HT\(_7\)-R biased ligands for the treatment of certain sleep disorders [18].

We have previously reported the synthesis and evaluation of the binding affinities of compounds 1a-c, with 1c, 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-2,3-dihydro-1H-inden-1-one (Fig. 2) having the highest affinity for the 5-HT\(_7\) receptor (\(K_i = 0.5\) nM) [19]. However, these indanone and tetrahydroisoquinoline (THIQ) linked analogs (1a-c) have a chiral center and the resulting enantiomers may differentially bind to the 5-HT\(_7\)-R. Thus, it was of interest to separate the enantiomers of 1c and identify the
eutomer to ascertain any such differential binding affinity and consequently their pharmacological action.

Using chiral chromatographic columns, we have been able to separate the enantiomers, but the isolated enantiomers were unstable even at a neutral pH and quickly reverted to the racemic mixture in a matter of hours. Thus, there was a need to redesign a new agent that could not undergo racemization and yet retain its binding affinity to the 5-HT7R. To accomplish this goal and to obtain analogs that retain selective binding to 5-HT7R, we designed and synthesized 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-2-methyl-2,3-dihydro-1H-inden-1-one (2) by replacing the acidic alpha proton of 1c with a methyl group and later, by a carboxyethyl group to obtain ethyl 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-1-oxo-2,3-dihydro-1H-indene-2-carboxylate (3).

Thus, in the current study, we report the discovery of (-)-5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-2-methyl-2,3-dihydro-1H-inden-1-one (2a) as a selective and β-arrestin biased 5-HT7R agonist for use as a pharmacological tool for further probing the 5-HT7 receptor.

Results and discussion

Chemistry

To obtain compound 2, the commercially available 5-chloroindanone 4a was treated with sodium hydride (NaH) and then diethyl carbonate to produce a β-keto ester 4b as reported in Scheme 1. Compound 4b was reacted with NaH and iodomethane to deliver a methyl group at the α-carbon of the β-keto ester, 4c. The methylated ester 4c was hydrolyzed and decarboxylated using acetic acid and concentrated HCl in a microwave assisted synthesis (MWAS) to afford ketone 4d. The ketone 4d was reacted with NaH and 1-bromo-2-chloro ethane to produce the alkylating agent 4e which was then coupled to 1,2,3,4-tetrahydro-isoquinoline (THIQ) under a general alkylating condition to afford the final product, 2 as a racemate. The free base was converted to the oxalate salt and the NMR and elemental (CHN) analysis confirmed the product as the desired compound.

Compound 2 satisfies all the criteria for Lipinski’s rule of five (Ro5) [15] except for the ClogP value of 5.2. Given the relatively high CLogP value, an additional analog was designed to reduce the CLogP value by replacing the lipophilic methyl group with a carboxethoxy group to form compound 3 (CLogP = 4.42), thus ensuring that this analog fully satisfy the Ro5.

The synthesis of 3, (Scheme 2), began with intermediate 4b obtained in Scheme 1, by initially treating it with NaH followed by 1-bromo-2-chloroethane to form alkylating agent 5a. Intermediate 5a was used to alkylate 1,2,3,4-tetrahydroisoquinoline (THIQ) under a microwave assisted condition to deliver the desired product, ethyl 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-1-oxo-2,3-dihydro-1H-indene-2-carboxylate, 3 which was subsequently converted to the oxalate salt.
Enantiomeric separation

The enantiomers of 2 were separated using high performance liquid chromatography (HPLC) with a semi-prep scale CHIRALPAK AD-H as reported previously [16]. Reinjection of the separated enantiomers on an analytical scale CHIRALPAK AD-H HPLC column indicated 100% enantiomeric purity for both (−)2 (2a), and (+)2 (2b). No racemization was subsequently observed, and the enantiomeric purity remained at 100%. Evaluation of the enantiomers in a Jasco P-1020 polarimeter at an average cell temperature of 23.5 °C and a wavelength of 589 nm indicated that the specific rotations [α] for the free base forms in ethanol were [α]D 25.5 (c 1.44, EtOH) = (−) 86.2 for 2a and [α]D 23.5 (c 1.49, EtOH) = (+) 93.3 for 2b.

Biological evaluation

Having obtained the desired target compound, 2 and its enantiomers (−)2 or 2a and (+)2 or 2b, and 3, the compounds were sent to the Psychoactive Drug Screening Program (PDSP) to screen for binding at relevant CNS receptors. The results are reported in Tables 1 and 2.

Compared to the standard drug clozapine, 2 binds with a 2-fold higher affinity at the 5-HT7R (Ki = 2.2 nM) and about 4-fold lower affinity than AS 19, a standard 5-HT7R agonist. In addition, compound 2 displays stereoselectivity with (−)2 displaying approximately twice the affinity as racemic 2 and >75 times higher affinity than (+)2 at the 5-HT7R. Furthermore, at the 5-HT1A receptor, (−)2 binds with about 20-fold affinity than racemic 2 (Table 1). Compound 2 also shows selectivity for the 5-HT7R when compared to other 5-HT receptors, Dopamine (DA) receptors and the three monoamine transporters (SERT, DAT, and NET) evaluated (Tables 1 and 2). The eutomer or the (−) enantiomer, 2a, was selective by over 100-fold for all the receptors and transporters evaluated except for the 5-HT1A receptor where the selectivity is greater by almost 72-fold (Tables 1 and 2). It is further noted that while the (+) enantiomer or the distomer (2b) has 25-fold less affinity for the 5-HT7R than the eutomer, it has in fact a higher affinity for the 5-HT2B (Ki = 59 nM), than for the 5-HT7R (Ki = 93 nM) (Table 1).

Table 1 Binding affinities of compounds and enantiomers at 5-HT receptors and SERT transporter

| Compound | Binding affinity constants, pKi ± SEM (Ki nM)a |
|----------|-----------------------------------------------|
|          | 5-HT1aR | 5-HT2aR | 5-HT3bR | 5-HT2cR | 5-HT2dR | SERT     |
| 2        | 5.87 ± 0.27 (1718) | 6.06 ± 0.06 (904) | 6.79 ± 0.05 (174) | 5.86 ± 0.07 (1735) | 8.65 ± 0.07 (2.2) | MT       |
| 2a. [−(−) 2] | 7.06 ± 0.07 (86.3) | 6.08 ± 0.06 (834) | 6.48 ± 0.04 (329) | MT | 8.94 ± 0.06 (1.2) | MT       |
| 2b. [+(+) 2] | 6.43 ± 0.06 (376) | 6.14 ± 0.06 (729) | 7.23 ± 0.04 (59) | 5.5 ± 0.08 (3130) | 7.09 ± 0.08 (93) | MT       |
| 1c.b | 7.81 ± 0.06 (16.0) | 6.6 ± 0.1 (748) | 6.96 ± 0.07 (109) | 6.89 ± 0.08 (128) | 9.33 ± 0.06 (0.5) | MT       |
| 3. | 7.30 ± 0.10 (52) | 7.42 ± 0.08 (38) | 7.79 ± 0.08 (16) | 6.05 ± 0.08 (885) | 8.47 ± 0.06 (3.4) | MT       |
| Clozapine | NR | NR | NR | NR | 8.30 ± 0.08 (5.0) | NR       |
| AS-19c | (89.7) | NS | NS | NS | (0.60) | NS       |
| Compound 7d | >10,000 | NR | NR | NR | 7.50 ± 0.10 (30) | NR       |

aMissed threshold of 50% inhibition at 10 µM concentration, NR Not reported, NS Not significant

b Reported in ref. [14]
c Reported in ref. [10] as a partial agonist with selectivity >100-fold at all 5-HTRs except for 5-HT1AR (Ki = 6.6 nM)
d Reported in ref. [18] as compound 1g

Table 2 Evaluation of the binding affinities of compound 2 and its enantiomers at DA receptors and other monoamine transporters (NET, DAT)

| Compound | Binding affinity constants, pKi ± SEM (Ki nM) of ligands at DARs, NET and DATa |
|----------|--------------------------------------------------------------------------------|
|          | D1 | D2 | D3 | D4 | D5 | NET | DAT |
| 2        | MT | 5.91 ± 0.06 (1225) | 6.76 ± 0.06 (185) | 6.01 ± 0.06 (1223) | MT | MT | MT |
| 2a. [−(−) 2] | MT | MT | MT | MT | MT | MT | MT |
| 2b. [+(+) 2] | MT | MT | MT | MT | MT | MT | MT |
| 3. | MT | 6.1 ± 0.1 (747) | 6.87 ± 0.08 (134) | MT | MT | MT | MT |

aMissed threshold of 50% inhibition at 10 µM concentration

Having obtained the desired target compound, 2 and its enantiomers (−)2 or 2a and (+)2 or 2b, and 3, the compounds were sent to the Psychoactive Drug Screening Program (PDSP) to screen for binding at relevant CNS receptors. The results are reported in Tables 1 and 2.

Compared to the standard drug clozapine, 2 binds with a 2-fold higher affinity at the 5-HT7R (Ki = 2.2 nM) and about 4-fold lower affinity than AS 19, a standard 5-HT7R agonist. In addition, compound 2 displays stereoselectivity with (−)2 displaying approximately twice the affinity as racemic 2 and >75 times higher affinity than (+)2 at the 5-HT7R. Furthermore, at the 5-HT1A receptor, (−)2 binds with about 20-fold affinity than racemic 2 (Table 1). Compound 2 also shows selectivity for the 5-HT7R when compared to other 5-HTRs, Dopamine (DA) receptors and the three monoamine transporters (SERT, DAT, and NET) evaluated (Tables 1 and 2). The eutomer or the (−) enantiomer, 2a, was selective by over 100-fold for all the receptors and transporters evaluated except for the 5-HT1A receptor where the selectivity is greater by almost 72-fold (Tables 1 and 2). It is further noted that while the (+) enantiomer or the distomer (2b) has 25-fold less affinity for the 5-HT7R than the eutomer, it has in fact a higher affinity for the 5-HT2B (Ki = 59 nM), than for the 5-HT7R (Ki = 93 nM) (Table 1).
Molecular modeling

To evaluate interaction of compounds with the 5-HT7R [13], we selected a homology model of the 5-HT7R published by Kim et al. [18] and the Induced Fit Docking (IFD) procedure was carried out on it, using default parameters. The model was first validated by docking AS-19 into it and replicating the appropriate interactions of the amino acid residues at the orthosteric site (Fig. 3) as reported [18]. To explore the difference in binding affinities and to predict which enantiomer 2S or 2R has interactions consistent with the binding affinities and β-arrestin recruitment, we evaluated the docking poses of 2S and 2R enantiomers in the homology model as shown in Fig. 4.

Evaluation of the interactions of 2S at the orthosteric site of the 5-HT7R revealed interactions with the key amino acid residues associated with β-arrestin biased signaling [18]. Thus, 2S has an ionic interaction with Asp 162, hydrogen bond interaction with Ile 233 through the oxygen of the carbonyl group but no interaction with Ser 243; these results are consistent with the interactions associated with β-arrestin recruitment as reported [18]. On the other hand, 2R had interaction with Asp 162, but no interaction with Ile 233 or Ser 243, leading to its prediction to have little or no β-arrestin recruitment capabilities.

Functional studies

The enantiomers of 2, i.e., 2a or the (−) enantiomer, and 2b, the (+) enantiomer were selected for evaluation for functional selectivity at the 5-HT7R. The ligands were tested using both Gs-mediated cAMP production assay and β-arrestin recruitment Tango assays in parallel and the results are reported in Table 3.

The results show that the (−) enantiomer 2a activates both G-protein and β-arrestin mediated signaling but acts more so as a β-arrestin biased agonist at the 5-HT7R (EC50 = 3.98 nM; Emax = 78.7%). In fact, 2a has a higher binding affinity (Ki = 1.2 nM), is much more potent and more efficacious at recruiting β-arrestin to the 5-HT7R than Compound 7 (Ki = 30 nM; EC50 = 162 nM; Emax = 62.8%), recently disclosed in the literature (Table 3) [18]. It is interesting to further note that 2a showed 8 times less activity than 5-HT for the Gs pathway, while it is over 31 times more potent than 5-HT in the β-arrestin pathway. The (+) enantiomer, 2b on the other hand, has over 30-fold weaker binding affinity at the 5-HT7R and displays less activity in recruiting β-arrestin to the 5-HT7R by over 39-fold (Table 3). Taken together, these results will predict (−) 2 or 2a to correspond to the 2S enantiomer while (+) 2 or 2b will correspond to the 2R enantiomer.

As indicated earlier, compound 3, with the carbethoxy replacement for the alpha methyl group of compound 2, was designed to improve hydrophilicity and comply with Lipinski’s Ro5 [15]. Compound 3 improved CLogP by 0.80 units to 4.42 and thus, satisfy Ro5 and was synthesized for screening. As shown in Table 1, the presence of the carbethoxy group in place of the methyl group did not weaken binding affinity to the 5-HT7R and in fact compound 3 has a similar binding affinity as compound 2 (Ki = 3.4 nM) and
even slightly better than that of clozapine (Ki = 5.0 nM) (Table 1).

In summary, 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-2-methyl-2,3-dihydro-1H-inden-1-one (2) was designed and synthesized to block the racemization of the previously reported alpha des-methyl analog, compound 1c. Following enantiomeric separation, 2a or (−) 2 has been shown not only to have retained binding affinity to the 5-HT7R but it has demonstrated significant β-arrestin biased functional selectivity at the receptor. In fact, while 2a showed 8 times less activity than 5-HT, for the Gs pathway, it showed over 31 times higher activity than 5-HT in the β-arrestin pathway. This β-arrestin pathway activity is more potent and more efficacious (2a; EC50 = 3.98 nM; Emax = 78.7%) than that of the recently published β-arrestin biased Compound 7 (EC50 = 162 nM; Emax = 62.7%) (Table 3). The molecular modeling results revealing interactions of 2a with appropriate amino acid residues at the orthosteric site of 5-HT7R suggest that the eutomer 2a corresponds to the 2S isomer. To improve the drug-like characteristics of 2, an additional analog, 3 with improved hydrophilicity and yet with similar binding affinities as 2 has been synthesized and reported in the present work.

### Materials and methods

Melting points were determined on a Gallenkamp (UK) apparatus and are uncorrected. All NMR spectra were obtained on a Varian 300 MHz Mercury Spectrometer and the free induction decay data were processed using Mestrelab’s Mnova NMR software (version 8.1) to obtain the reported NMR data. Elemental analyses were carried out by Atlantic Microlab, Inc., Norcross, GA, and are within 0.4% of theory unless otherwise noted. Flash chromatography was performed using a Teledyne CombiFlash® with Davisi grade 634 silica gel. Starting materials and solvents were obtained from Sigma Aldrich and were used without further purification. All microwave assisted syntheses (MWAS) were carried out using a Biotage Initiator® equipment.

### Synthetic chemistry

#### Synthesis of 5-chloro-2-(2-(3,4-dihydroisoquinolin-2(1H)-yl)ethyl)-2-methyl-2,3-dihydro-1H-inden-1-one, 2

Synthesis of ethyl 5-chloro-1-oxo-2,3-dihydro-1H-indene-2-carboxylate, 4b A modified method described by Paccani and co-workers [20] was followed to access the 5-substituted β-keto ester 4b. (Scheme 1). In brief, a solution of 5-chloroindanone 4a, (100 mmol) in diethyl carbonate (50 mL) was added dropwise to a stirred suspension of sodium hydride (NaH) (200 mmol, 60% in mineral oil previously washed with hexanes) in diethyl carbonate (DEC) (25 mL) at 0 °C with stirring (note green coloration). When evolution of gas has ceased, the mixture was allowed to stir at room temperature overnight then diluted with dichloromethane (CH2Cl2) and treated with aqueous acetic acid solution. The aqueous phase was separated and extracted with CH2Cl2. The combined organic extract was dried with anhydrous sodium sulfate (Na2SO4) and concentrated under reduced pressure to yield a thick brown crude oil. The crude oil was loaded onto a cartridge and purified on a Combiflash chromatographic equipment using a gradient elution (up to 10% EtOAc in hexanes) to afford ethyl 5-chloro-1-oxo-2,3-dihydro-1H-indene-2-carboxylate, 4b as needle-like white crystals. Yield: 89%.

### table: Table 3 Evaluation of the functional selectivity of compounds 2a and 2b at the 5-HT7 receptor

| Compound/Activity | 5-HT7 receptor | cAMP | β-arrestin |
|-------------------|----------------|------|------------|
|                   | pKi_pEC50 | Emax | pKi_pEC50 | Emax | pEC50 | Hill |
| 2a                | 8.94 ± 0.06 (1.2) | 82.8 ± 2.6 | 6.9 ± 0.3 (126) | 1.3 ± 0.2 | 78.7 ± 5.7 | 8.4 ± 0.1 (3.98) | 1.2 ± 0.1 |
| 2b, Agonist       | 7.1 ± 0.2 (80.7) | ND | ND | ND | 43.2 ± 9.0 | 6.8 ± 0.2 (158) | 1.0 ± 0.1 |
| 2b, Inv Agonist   | −4.8 ± 2.2 | 6.7 ± 0.1 (203) | 1.15 ± 0.2 | ND | ND | ND |
| 2b, Antagonist    | 100 | 6.4 ± 0.1 (406) | 1.9 ± 0.2 | ND | ND | ND |
| 5-HT              | 8.9 ± 0.2 (1.3) | 100 | 7.8 ± 0.1 (15.3) | 1.0 ± 0.1 | 100 | 6.9 ± 0.1 (125) | 3.4 ± 0.4 |
| Compound 7b       | 7.5 ± 0.1 (30) | 94.7 | 5.1 ± 0.1 (7788) | NR | 62.7 | 6.8 ± 0.2 (162) | NR |

NR Not reported. ND Experiment was conducted but no antagonism was measured. NA Experiment was not conducted

a Enantiomers (2a and 2b) were tested in both Gs-cAMP and β-arrestin recruitment (Tango) assays and the results are reported as mean ± SEM from a minimum of 3 independent assays, each in triplicates

b Data was obtained from ref. [18]
**Synthesis of ethyl 5-chloro-2-methyl-1-oxo-2,3-dihydro-1H-indene-2-carboxylate, 4c** To a suspension of hexane-washed NaH (60% in mineral oil, 12 mmol) in dry dimethyl formamide (DMF) was added a solution of the 5-substituted β-keto ester 4b (10 mmol) dropwise with stirring (note the green coloration) over 30 min. After the evolution of gas has ceased, 1-bromo-2-chloroethane (20 mmol) (Scheme 1) was added dropwise and allowed to stir for 24 h. After the reaction was quenched in water (100 mL) and extracted with CH₂Cl₂ (2 × 100 mL), the organic layers were combined, washed with brine (100 mL), and dried over Na₂SO₄. The resulting solution was concentrated in-vacuo to produce a thick oily crude product. The crude was ash column chromatography using gradient EtOAc gradient up to 70% EtOAc) to afford the compound as white crystals. Yield: 55%, mp: 205–206 °C. ¹H NMR (300 MHz, DMSO-d₆) δ 11.15 (s, 2H), 7.77–7.54 (m, 2H), 7.54–7.37 (m, 1H), 7.28–7.00 (m, 4H), 4.15 (s, 2H), 3.33–3.13 (m, 3H), 3.13–2.84 (m, 5H), 2.10–1.87 (m, 2H), 1.14 (s, 3H). ¹³C NMR (75 MHz, DMSO-d₆) δ 208.33, 164.69, 154.78, 140.65, 133.98, 132.30, 130.16, 128.88, 128.64, 127.65, 127.50, 126.93, 126.78, 125.80, 52.72, 52.13, 49.40, 47.71, 32.09, 31.13, 25.91, 23.70. Anal. Calcd for C₁₇H₁₄Cl₂O₆: C, 56.80; H, 3.93; N, 2.74. Found: C, 56.97; H, 4.08; N, 2.77.

**Synthesis of 5-chloro-2-(2-chloroethyl)-2-methyl-2,3-dihydro-1H-inden-1-one, 2** Oxalate A mixture of 5-chloro-2-(2-chloroethyl)-2-methyl-2,3-dihydro-1H-inden-1-one, 4e (2.05 mmol), THIQ (2.26 mmol), potassium carbonate (K₂CO₃, 2.26 mmol), and KI (catalytic amount) in dimethoxethane (DME, 10 mL) was placed in a 20 mL microwave vial with a stirrer and tightly sealed. The mixture was subjected to microwave heating at 120 °C for 60 mins. The crude mixture was purified on silica gel by flash chromatography (hexanes: EtOAc gradient up to 70% EtOAc) to afford the compound as its free base. The free base was converted to the oxalate salt and crystallized from methanol-diethyl ether (MeOH- Et₂O) as white crystals. Yield: 55%, mp: 205–206 °C. ¹H NMR (300 MHz, DMSO-d₆) δ 11.15 (s, 2H), 7.77–7.54 (m, 2H), 7.54–7.37 (m, 1H), 7.28–7.00 (m, 4H), 4.15 (s, 2H), 3.33–3.13 (m, 3H), 3.13–2.84 (m, 5H), 2.10–1.87 (m, 2H), 1.14 (s, 3H). ¹³C NMR (75 MHz, DMSO-d₆) δ 208.33, 164.69, 154.78, 140.65, 133.98, 132.30, 130.16, 128.88, 128.64, 127.65, 127.50, 126.93, 126.78, 125.80, 52.72, 52.13, 49.40, 47.71, 32.09, 31.13, 25.91, 23.70. Anal. Calcd for C₁₉H₁₃Cl₂O₆: C, 56.80; H, 3.93; N, 2.74. Found: C, 56.97; H, 4.08; N, 2.77.

**Ethyl 5-chloro-2-(3,4-dihydroisoquinolin-2(1H)-yl)(ethyl)-2,3-dihydro-1H-indene-2-carboxylate, 3 oxalate** To a suspension of hexane-washed NaH (60% in mineral oil, 12 mmol) in dry DMF was added a solution of the ethyl 5-chloro-1-oxo-2,3-dihydro-1H-indene-2-carboxylate, 3 (0.5 mmol) dropwise with stirring (note the green coloration) over 30 min. After the evolution of gas has ceased, 1-bromo-2-chloroethane (20 mmol) (Scheme 1) was added dropwise and allowed to stir for 24 h. After the reaction was quenched in water (100 mL) and extracted with CH₂Cl₂ (2 × 100 mL), the organic layers were combined, washed with brine (100 mL) and dried over Na₂SO₄. The resulting solution was concentrated in-vacuo to obtain the crude product 4e, as a clear yellowish oil (45% overall yield). ¹H NMR (300 MHz, CDCl₃) δ 7.66 (d, J = 8.4 Hz, 1H), 7.42 (s, 1H), 7.34 (d, J = 8.0 Hz, 1H), 3.56–3.42 (m, 2H), 3.18 (d, J = 16.9 Hz, 1H), 2.92 (d, J = 17.9 Hz, 1H), 2.10 (t, J = 8.4 Hz, 2H), 1.22 (s, 3H). ¹³C NMR (75 MHz, CDCl₃) δ 208.15, 153.59, 141.67, 133.70, 128.51, 126.79, 125.55, 48.76, 40.52, 40.48, 40.28, 23.63.
was added dropwise and allowed to stir for 18–24 h. After, the reaction was quenched in water (100 mL), extracted with CH₂Cl₂ (2 × 100 mL), the organic layers were pulled together, washed with brine, and dried over Na₂SO₄ and concentrated in-vacuo to obtain the crude product, 5a which was then used directly in the next step without further purification.

A mixture of alkylation agent, 5a (1.66 mmol), THIQ (1.82 mmol) NaHCO₃ (1.82 mmol), and KI (catalytic) in DME or Toluene (10 mL) was placed in a 20 mL microwave vial with a stirrer and tightly sealed. The mixture was subjected to microwave heating at 120 °C for 60 min, allowed to cool to room temperature and the mixture was subjected to microwave heating at 120 °C for 5a product, Na₂SO₄ and concentrated in-vacuo to obtain the crude product, 5a which was then used directly in the next step without further purification.

Enantiomeric separation

The separation of the enantiomers was accomplished using HPLC with a semi-prep scale CHIRALPAK AD-H 1.0 × 25 cm column, 95:5:0.1 Hex:EtOH:diethylamine (DEA) mobile phase, 4.7 mL/min flowrate, and 254 nm analysis wavelength and was reported previously [16].

Biological evaluation

Receptor binding affinity studies

Binding affinities reported in were conducted by the National Institute of Mental Health Psychoactive Drug Screening Program (NIMH-PDSP). Details of the methods and radioligands used for the binding assays were previously reported [21], and a list of receptors and radioligands used in the binding affinity evaluations are reported in Table 4.

| Receptor  | 5-HT₁AR | 5-HT₂AR | 5-HT₃AR | 5-HT₄R | 5-HT₇R |
|-----------|---------|---------|---------|---------|---------|
| Radioligand | [3H]8-OH-DPAT | [3H]Ketanserin | [3H]LSD | [3H]Mesulergine | [3H]LSD |
| Receptor | D₁R | D₂R | D₃R | D₄R | D₅R |
| Radioligand | [3H]SCH23390 | [3H]N-Methylspiperone | [3H]N-Methylspiperone | [3H]N-Methylspiperone | [3H]N-Methylspiperone |
| Receptor | SERT | NET | DAT | DAT | DAT |
| Radioligand | [3H]Citalopram | [3H]Nisoxetine | [3H]WIN35428 | [3H]WIN35428 | [3H]WIN35428 |

GPCR Tango assays: G-protein independent β-arrestin recruitment

Recruitment of β-arrestin to agonist stimulated 5-HT7R were performed using the “Tango”-type assay described in Barnea et al. [22] with modifications, to evaluate 2a and 2b. GPCR Tango assay for measuring G-protein independent β-arrestin recruitment was carried out by the NIMH-PDSP as per their protocol with some modifications in the Tango assay system reported previously [21, 22]. GPCR Tango constructs were codon optimized for better expression in mammalian cell lines and total synthesis was by Blue Heron Biotech (Bothell, WA) with independent sequencing confirmation [23]. HTLA cells (an HEK293 cell line stably expressing a tTA-dependent luciferase reporter and a β-arrestin2-TEV fusion gene) were maintained in DMEM supplemented with 10% FBS and 2 μg/ml Puromycin and 100 μg/ml Hygromycin. The FLAG tag was designed into the GPCR Tango constructs for confirmation of surface expression and comparison of expression levels. HTLA cells were transfected using calcium phosphate transfection method [24–26] with GPCR tango constructs. Briefly, HTLA cells were sub-cultured into 10-cm dishes (3 × 10⁶ cells per dish) and incubated overnight. For transfection in each 10-cm dish, 10 μg receptor DNA construct in 440 μl distilled water was mixed with 60 μl of 2 M CaCl₂ and the DNA/CaCl₂ solution was then added dropwise into 500 μl 2x HBS solution (50 mM HEPES, 280 mM NaCl, 10 mM KCl, 1.5 mM Na₂HPO₄, pH 7.00) while shaking. The mixture was incubated at room temperature for 10 min, then added to the cells dropwise and incubated overnight. Transfected HTLA cells were plated in DMEM supplemented with 1% dialyzed FBS in Poly-L-Lys-coated 384-well white clear bottom cell culture plates at a density of 15,000 cells per well (40 μl). Cells were incubated for a minimum of 6 h or overnight before drug simulation treatments. Drug stimulation solutions prepared in sterile-filtered
Tango assay buffer at 5x concentration were added to cells at 10 µl per well and incubated overnight. Antagonist activity was measured by pre-incubation of drug solutions (6x of the final concentration) with cells for 30 min before addition of 10 µl of a final EC80 concentration of reference agonist. The EC80 concentration was determined in separate preliminary dose-response assays. On the day of measurement, medium and drug solutions were removed and BrightGlo reagent (Promega), 20 µl per well (diluted 20-fold with Tango assay buffer) were added. Plates were incubated for 20 min at room temperature in the dark followed by chemiluminescence measurement. The chemiluminescence data was recorded using Luminescence counter and reported as relative luminescence units.

HEK-5-HT7A/cAMP functional assay

Human embryonic kidney cells were transfected with 10 µg h5-HT7A cDNA using PEI in unsupplemented DMEM. After 5 h, cells were plated at a density of 200,000 cells per well in 48 well plates in DMEM supplemented with 10% charcoal-stripped FetalClone and pen-strep. The medium was removed about 18 h later. For agonist assays, 0.9 ml EBSS (116 mM NaCl, 22 mM glucose, 15 mM HEPES, 8.7 mM NaH2PO4, 5.4 mM KCl, 1.3 mM CaCl2, 1.2 mM MgSO4, 1 mM ascorbic acid, 0.5 mM IBMX [3-isobutyl-1-methyl-xanthine] without BCS, pH 7.4 at 37 °C) was added. After 5 h, cells were plated at a density of 200,000 cells per well in 48 well plates in DMEM supplemented with 10% charcoal-stripped FetalClone and pen-strep. The medium was removed about 18 h later. For agonist assays, 0.9 ml EBSS (116 mM NaCl, 22 mM glucose, 15 mM HEPES, 8.7 mM NaH2PO4, 5.4 mM KCl, 1.3 mM CaCl2, 1.2 mM MgSO4, 1 mM ascorbic acid, 0.5 mM IBMX [3-isobutyl-1-methyl-xanthine] without BCS, pH 7.4 at 37 °C) was added. After 20 min, the compound was added in a final volume of 1 ml, and incubated for 20 min. For antagonists, 0.8 ml EBSS is added, cells were incubated for 10 min, the compound was added, and incubated for 10 min after which serotonin (100 nM) was added. For all conditions, after 20 min incubation with agonist, the reaction was terminated by aspiration of the buffer, and 0.1 ml trichloroacetic acid was added. Plates were incubated for 2 h on a rotator. Adenylate cyclase activity was measured using a cyclic AMP EIA kit (Cayman). Aliquots (40 µl) of each well were diluted to 200 µl with EIA buffer from the kit, and 50 µl of the dilution was added to the EIA plate. After addition of tracer and monoclonal antibody, the EIA plates were incubated for 18 h at 4 °C. The reaction was aspirated, plates were washed 5 x 300 µl with wash buffer, and Ellman’s reagent was added. After a 2-h incubation in the dark on a rotator, the plates were read at 410 nm. Basal cAMP is subtracted from all values. 5-HT7 agonists stimulate cAMP formation, maximal stimulation was defined with 10 µM serotonin. The maximal drug effect is normalized to maximal serotonin effect in the tables.

Molecular modeling

The target compounds AS-19, 2a and 2b were optimized using the LigPrep tool and energy minimized using the OPLS3e force field in Schrodinger’s Small-Molecule Drug discovery suite [17, 27–30]. The individual compounds in their protonated forms were docked into the homology model of the 5-HT7R using the IFD workflow and the results depicted in Figs. 3, 4.

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Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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