

Targeting the Serotonin 5-HT₇ Receptor in the Search for Treatments for CNS Disorders: Rationale and Progress to Date

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Abstract The 5-HT₇ (5-hydroxytryptamine 7, serotonin 7) receptor is one of the most recently identified members of the serotonin receptor family. Pharmacological tools, including selective antagonists and, more recently, agonists, along with 5-HT₇ receptor (5-HT₇R) knock-out mice have revealed the involvement of this receptor in central nervous system processes. Its well-established role in controlling body temperature and regulating sleep and circadian rhythms has implicated this receptor in mood disorders. Thus, the 5-HT₇R has gained much attention as a possible target for the treatment of depression. Although preclinical data support the antidepressant-like actions of 5-HT₇R antagonists, their clinical efficacy has not been yet established. Other evidence has implicated the 5-HT₇R in learning and memory. Preclinical findings suggest that blockade of this receptor may be beneficial against schizophrenia-like cognitive deficits. Other possible indications include nociception, epilepsy, migraine, autism spectrum disorders, and Rett Syndrome. However, the question is whether the beneficial effects may be achieved by activation or blockade of 5-HT₇Rs. Hence, this review briefly summarises the recent findings on the role of 5-HT₇Rs and their ligands in CNS disorders.

Key Points

5-hydroxytryptamine 7 (5-HT₇) receptors not only play a physiological role in the regulation of the central nervous system (CNS) but also may be involved in pathological processes.

Thus, these receptors represent a potential therapeutic target for treating CNS disorders.

However, whether therapeutic efficacy can be achieved via activation or blockade of the 5-HT₇ receptor remains uncertain.

1 Introduction

The 5-hydroxytryptamine 7 receptor (5-HT₇R) was cloned in 1993 by independent laboratories [1–3]. To date, several splice variants have been described [4, 5], but the only functional difference that has been reported so far is a differential pattern of receptor internalisation displayed by the human 5-HT₇R (d) isoform [6]. This receptor, belonging to the G-protein-coupled receptor (GPCR) superfamily, is positively coupled to adenylyl cyclase through the stimulatory G α s proteins, and its activation results in an increase in cyclic adenosine monophosphate (cAMP). In addition, it has been recently demonstrated that the 5-HT₇R interacts not only with the G α s but also with G α 12 proteins [7]. The dynamic palmitoylation can represent a molecular mechanism responsible for selective G α s- or G α 12-mediated signalling [8]. Recent evidence suggests that 5-HT₇R/G α 12 signalling in the hippocampus undergoes strong developmental regulation with a pronounced transient

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increase during early postnatal stages and may represent a molecular mechanism by which serotonin specifically modulates the formation of initial neuronal networks [9]. The pharmacology and signal transductions of 5-HT₇Rs may be even more complicated, as it has been recently demonstrated that these receptors may form homodimers [10]; the heterodimerisation with 5-HT_{1A}R has also been reported [11].

2 Ligands of 5-HT₇ Receptors

Several 5-HT₇R antagonists are available, including the nonselective antagonist DR-4004 [12] and several selective antagonists such as SB-258719 [13], SB-269970 [14], SB-656104 [15] and JNJ-18038683 [16] (Table 1). In the absence of selective agonists of 5-HT₇Rs, unselective compounds such as 5-carboxamidotryptamine or 8-hydroxy-2-(dipropylamino)tetralin (8-OH-DPAT) (5-HT_{1A/7}R agonist) have often been used. More recently, various selective 5-HT₇R agonists have been identified (reviewed in detail by Di Pilato et al. [17]), including AS-19 [18], LP-44 [19], LP-12 [19], LP-211 [20], and E-55888 [18] (Table 1). The purpose of this review is to summarize existing data on the effects of 5-HT₇R ligands in animal models of central nervous system (CNS) disorders. When available, clinical data are also discussed.

3 Depression

A converging body of evidence has shown that the selective blockade of 5-HT₇Rs displays an antidepressant-like activity in commonly used preclinical tasks, i.e. in the tail suspension test (TST) in mice as well as in the forced swim test (FST) in both mice and rats [16, 21–26]. Specifically, 5-HT₇R knock-out (KO) mice showed an antidepressant-like behavioural profile as revealed by reduced immobility in the FST and TST [21–23]. In line with genetic inactivation effects, the pharmacological blockade of 5-HT₇Rs by the selective antagonist SB-269970 also exerted antidepressant-like activities in the TST [22, 24, 25] as well as in the FST in both mice [22, 25] and rats [26]. JNJ-18038683 was also effective in the mouse TST [16]. Moreover, the efficacy of SB-269970 was also assessed in the olfactory bulbectomy paradigm, which is considered a behavioural model of agitated depression [27]. Interestingly, SB-269970 produced a faster antidepressant-like response than the commonly prescribed selective serotonin reuptake inhibitor (SSRI) antidepressant fluoxetine.

In addition to exerting a distinct antidepressant-like action, the blockade of 5-HT₇Rs may also augment the behavioural effects of antidepressant drugs. For example,

SB-269970, administered at a dose not exerting a significant antidepressant effect, enhanced the action of sub-effective doses of antidepressant drugs, including the SSRI citalopram, in the TST and FST in mice [23, 24, 28].

5-HT₇R may also represent a clinically relevant target for the treatment of depression. It has been suggested that the clinically established antidepressant effect of certain antipsychotics, such as amisulpride, aripiprazole or lurasidone, is most likely mediated by the 5-HT₇R [23, 29, 30]. In fact, functional 5-HT₇Rs were required to reveal the antidepressant-like effects of those drugs in the TST and FST in mice [23, 29, 30]. Moreover, one clinical study evaluated the efficacy of JNJ-18038683, a selective antagonist of 5-HT₇Rs, as an antidepressant in patients with major depressive disorder [16]. There was no statistically significant improvement over a placebo on the Montgomery-Åsberg Depression Rating Scale (MADRS) after either JNJ-18038683 or escitalopram administration. Thus, due to a lack of assay sensitivity, the interpretation of these results is inconclusive.

4 Stress

Prolonged stress is a major risk factor for depression, and stress-based animal models represent a useful instrument for mimicking depressive-like symptomatology [31]. It has been proposed that the modulatory role for serotonin in the stress-evoked hypothalamic-pituitary-adrenal axis response may involve 5-HT₇Rs [32]. Recent data suggest that chronic restraint stress-induced endocrine disruption may be associated with the increased function and expression of 5-HT₇Rs [33]. Consequently, pharmacological blockade of adrenocortical 5-HT₇Rs could be of therapeutic benefit for overcoming endocrine disruption in stress-related diseases. Moreover, 5-HT₇Rs may also be involved in the response of neural circuits to repeated stress. Repeated corticosterone administration, a model known to mimic some aspects of stress exposure, increased the reactivity of rat CA3 hippocampal circuitry to the activation of 5-HT₇Rs [34]. Moreover, the selective 5-HT₇R antagonist SB-269970 counteracted restraint stress-induced attenuation of long-term potentiation in the rat frontal cortex [35]. It has also been demonstrated that exposure to chronic mild stress evokes up-regulation of 5-HT₇R messenger RNA (mRNA) in the rat hippocampus and hypothalamus, and these changes were counteracted by the antidepressant fluoxetine [36]. In addition, data from our laboratory indicate that the administration of SB-269970 reversed the stress-induced cognitive deficit in rats [37]. In line with data demonstrating that selective blockade of 5-HT₇Rs augmented the behavioural effects of antidepressants, SB-269970, administered at an inactive dose, enhanced the pro-cognitive

Table 1 The behavioural effects of 5-HT₇Rs ligands

Compound/ indication	Effect	Dose ^a	References
5-HT₇R antagonists			
SB-258719: 3-methyl-N-[(1 R)-1-methyl-3-(4-methyl-1-piperidinyl)propyl]-N-methylbenzenesulfonamide			[13]
Epilepsy	Antiepileptic activity in the WAG/Rij rat model of absence epilepsy	10	[93]
SB-258741: R-(+)-1-(toluene-3-sulfonyl)-2-[2-(4-methylpiperidin-1-yl)ethyl]-pyrrolidine			[110]
Schizophrenia	Reversal of amphetamine-induced hyperactivity	2.3–9.1	[75]
	Normalisation of PCP-disrupted PPI	2.3–9.1	[75]
SB-269970: (2 R)-1-[(3-hydroxyphenyl)sulfonyl]-2-[2-(4-methyl-1-piperidinyl)ethyl]pyrrolidine			[14, 110]
Depression	Antidepressant-like effect in the FST and TST in mice	10	[22]
	Antidepressant-like effect in the TST in mice	3–30	[24]
	Antidepressant-like effect in the FST and TST in mice	5–10	[25]
	Antidepressant-like effect in the FST in rats	1.25–2.5	[26]
	Antidepressant-like effect in olfactory bulbectomised rats	2	[27]
Sleep	REM sleep-suppressive effect in rats	10	[24]
	REM sleep-suppressive effect in rats	10–20	[39]
Circadian rhythms	Blockade of 8-OH-DPAT-induced a phase advance in the rat SCN slices	0.01 μM	[44]
Anxiety	Anxiolytic-like effects in the Vogel drinking test and the elevated plus-maze test in rats as well as in the four-plate test in mice	0.5–1	[25]
OCD	Reduced marble burying in mice	10	[53]
Cognition	Improvement of reference memory in a radial arm maze task in rats	1	[67]
	Deficit in novel location test in mice	10	[56]
	Improvement of cognitive flexibility in the ASST in rats	1	[37]
	Improvement of object recognition memory in the NORT in rats	30	[58]
	Deficits in object recognition memory in the NORT in mice	3–10	[59]
Schizophrenia	Reversal of amphetamine- and ketamine-induced hyperactivity in mice	10–30	[74]
	Reversal of PCP-induced hyperactivity in rats	30	[58]
	Reversal of the amphetamine-induced PPI deficits in mice	30	[74]
	Reversal of MK-801-induced deficits in an autoshaping Pavlovian instrumental learning task in rats	3–10	[81]
	Reversal of intra-prefrontal ketamine-induced deficits in rats' autoshaping Pavlovian instrumental learning task	1 μg	[82]
	Reversal of the PCP-induced deficits in reversal learning	3–10	[79]
	Reversal of the MK-801-induced impairment in working memory on a rat delayed non-matching to position task	10	[80]
	Reversal of PCP-induced deficits in the NORT in rats	1	[83]
	Reversal of ketamine-induced deficits in the NORT in rats	1	[77]
	Reversal of ketamine-induced cognitive inflexibility on the ASST in rats	1	[77]
	Reversal of ketamine-induced social withdrawal in rats	1	[77]
Epilepsy	Antiepileptic activity in a pilocarpine-induced rat model of temporal lobe epilepsy	10	[94]
Migraine	Inhibition the 5-CT-induced dilatation in the middle meningeal artery in rats	1	[100]
	Reduction of neurogenic dural vasodilation in rats	5–10	[101]
SB-656104: 6-[(R)-2-[2-[4-(4-chlorophenoxy)-piperidin-1-yl]-ethyl]-pyrrolidine-1-sulfonyl]-1 H-indole			[15]
Sleep	REM sleep-suppressive effect in rats	30	[15]
Schizophrenia	Reversal of MK-801-induced learning and memory impairments in the passive avoidance and Morris water maze tests in rats	10–30	[84]
JNJ-18038683: 3-(4-chlorophenyl)-1,4,5,6,7,8-hexahydro-1-(phenylmethyl)pyrazolo[3,4-d]azepine 2-hydroxy-1,2,3-propanetricarboxylate			[16]

Table 1 continued

Compound/ indication	Effect	Dose ^a	References
Depression	Antidepressant-like effect in the TST in mice	0.3–1	[16]
Sleep	REM sleep-suppressive effect in rats	1–10	[16]
	REM sleep-suppressive effect in healthy human volunteers	20 mg	[16]
Circadian rhythms	Blockade of 8-OH-DPAT-induced and photic phase shifts of wheel running activity in mice	10	[45]
5-HT₇R agonists			
AS-19: [(2 S)-(+)-5-(1,3,5-trimethylpyrazol-4-yl)-2-(dimethylamino)tetralin]			[18]
Cognition	Improvement of long-term memory but impairment of short-term memory in an autoshaping Pavlovian/instrumental learning task in rats	1–10	[62, 63]
Circadian rhythms	Shortened the period length of PER2 bioluminescence in explants of SCN from PER2::LUC mice	0.01–0.1 μM	[47]
Pain	Reversal of capsaicin-induced mechanical hypersensitivity in mice	3–10	[18]
	Hyperalgesic effects in a mice model of nerve injury	0.1–10	[88]
	Hyperalgesic effects in a rat model of nerve injury	2.5–10	[89]
	Reversal of thermal hyperalgesia in streptozotocin-induced experimental diabetes in mice	10	[90]
Epilepsy	Pro-epileptic activity in a pilocarpine-induced rat model of temporal lobe epilepsy	10	[94]
Migraine	Increase in neurogenic dural vasodilation in rats	5–10	[101]
LP-211: <i>N</i> -(4-cyanophenylmethyl)-4-(2-diphenyl)-1-piperazinehexanamide]			[20]
Sleep	REM sleep-suppressive effect in rats	5–10	[41]
Circadian rhythms	Induction of phase advance in mice	0.25	[46]
Anxiety	Anxiolytic-like effects in the black and white box test and the dark/light test in mice	0.25	[46]
Cognition	Improvement of long-term memory in an autoshaping Pavlovian/instrumental learning task	1	[64]
Rett syndrome	Reversal of anxiety-related behaviour in a light/dark test, motor performance in a Dowel test and memory deficits in the novelty preference task in a mice model of the Rett syndrome	0.25	[99]
E-55888: dimethyl-[2-[3-(1,3,5-trimethyl-1 H-pyrazol-4-yl)-phenyl]-ethyl]amine]			[18]
Pain	Reversal of capsaicin-induced mechanical hypersensitivity in mice	3–10	[18]
	Increase of the analgesic potency of morphine	10	[111]
	Hyperalgesic effects in a rat model of nerve injury	10	[89]

Only studies demonstrating efficacies (or impairing effects) are included

ASST attentional set-shifting task, *FST* forced swim test, *NORT* novel object recognition test, *OCD* obsessive-compulsive disorder, *PCP* phencyclidine, *PPI* prepulse inhibition, *REM* rapid eye movement, *SCN* suprachiasmatic nuclei, *TST* tail suspension test, *5-CIT* 5-carboxamidotryptamine

^a Doses are mg/kg unless otherwise indicated

efficacy of an inactive dose of the SSRI escitalopram [37]. Thus, the stress-evoked enhancement of 5-HT₇R-mediated responses or up-regulation of their expression may purportedly account for the efficacy of the 5-HT₇R antagonist in ameliorating stress-induced abnormalities. Nevertheless, it should be noted that the relation between stress, glucocorticoids and 5-HT₇R expression and function seems to be far more complex [32].

5 Sleep and Circadian Rhythm Regulation

The role for the 5-HT₇R in mood disorders is closely linked to the regulation of sleep and circadian rhythms [38]. Similar to the actions of antidepressant drugs, the

blockade of 5-HT₇R was shown to alter rapid eye movement (REM) sleep parameters in the opposite direction to the abnormalities found in depression patients. Specifically, 5-HT₇R KO mice spent less time in and demonstrated less frequent episodes of REM sleep [22]. Similar changes in REM sleep patterns were demonstrated after administration of 5-HT₇R antagonists, including SB-269970, SB-656104 and JNJ-18038683 [24, 39]. Moreover, both genetic inactivation and pharmacological blockade augmented the effects of SSRIs on REM sleep suppression [24, 40]. The effect of a 5-HT₇R blockade on REM sleep translates from rodent to humans, as JNJ-18038683 was also found to increase REM latency and decrease REM sleep duration in healthy volunteers [16]. Of note is the recent observation that the 5-HT₇R agonist LP-211 also

suppressed REM sleep [41]. It has been proposed that activation of 5-HT₇Rs expressed by γ -aminobutyric acid (GABA)-ergic interneurons decreases the activity of REM sleep-promoting cholinergic neurons in the laterodorsal and pedunculopontine tegmental (LDT/PPT) nuclei and reduces REM sleep (reviewed by Monti and Jantos [38]). On the other hand, suppression of REM sleep by 5-HT₇R antagonists may involve the reduction of GABA-induced inhibition of serotonergic cells that leads to the increase of 5-HT release at postsynaptic sites critical for REM sleep occurrence, including the LDT/PPT nuclei [39].

5-HT₇Rs have also been implicated in the regulation of the mammalian circadian clock located in the suprachiasmatic nuclei (SCN). *In vitro* and *in vivo* studies have demonstrated that 8-OH-DPAT-induced non-photic phase resetting was mediated by the 5-HT₇R, as the shift was blocked by genetic inactivation or antagonists of those receptors, including SB-269970, DR-4004 and JNJ-18038683 [21, 42–45]. In line with these data, a selective agonist of 5-HT₇Rs, LP-211, induced a phase advancement on spontaneous circadian rhythm in mice [46]. Moreover, another 5-HT₇R agonist, AS19, shortened the period length of PER2 bioluminescence in explants of SCN from PER2::LUC mice genetically modified to report changes in the expression of a key clock protein [47]. This reduction was blocked by SB-269970, a selective 5-HT₇R antagonist.

The 5-HT₇R is probably also involved in 5-HT-mediated suppression of photic activation of the SCN [48]. However, a 5-HT₇R agonist, AS-19, failed to inhibit light-induced phase shifts [49]. The lack of effect may be ascribed to the low efficacy of the tested compound [50].

It has also been suggested that a multimodal approach based on a combination of SSRIs and 5-HT₇R antagonists may be beneficial in treating patients suffering from poor circadian rhythm synchrony. In rodent models, the combination of escitalopram and SB-269970 produced a greater impact on circadian rhythms than that observed with either agent alone [47]. In this study, combination of inactive doses of escitalopram (2.5–10 mg/kg) and SB-269970 (10–30 mg/kg) produced robust phase delays in rats given access to running wheels. In line with these data, vortioxetine, the SSRI exhibiting antagonistic affinity for 5-HT₇Rs, produced an increase in circadian period length in tissue explants from the SCN of PER2::LUC mice and induced a phase delay in wheel-running behaviour in rats, and this effect was blocked by AS19 [51].

6 Anxiety

In contrast to the well-established role for 5-HT₇Rs in depression, their involvement in the regulation of anxiety-like behaviours is less consistent. No differences in assays

sensitive to anxiety states, that is, in the elevated plus maze or light/dark transfer test, were observed between 5-HT₇R KO mice and wild-type (WT) controls [21, 52]. On the other hand, SB-269970 exerted specific anti-anxiety-like effects in the Vogel conflict test and the elevated plus maze test in rats, as well as in the four-plate test in mice [25]. Moreover, SB-269970 reduced marble burying in mice, a behaviour linked to obsessive-compulsive disorder and anxiety [53]. Nevertheless, the compound's efficacy in this test probably reflects antidepressant-like activity. It has also been reported recently that LP-211, an agonist of 5-HT₇Rs, reduces anxiety-like behaviour in the black and white box test and the dark/light test in mice [46]. Moreover, rats chronically treated during adolescence with LP-211 showed reduced anxiety-related behaviour in adulthood [54].

7 Cognition

It has been demonstrated that the 5-HT₇R is involved in hippocampal-dependent cognitive processes (reviewed by Roberts and Hedlund [55]). Accordingly, 5-HT₇R KO mice demonstrated impairments of contextual hippocampal-dependent learning and displayed decreased long-term synaptic plasticity within the CA1 region of the hippocampus [52]. Moreover, hippocampus-associated spatial memory deficits in the novel location test were demonstrated in mice with either genetic or pharmacological inactivation of 5-HT₇Rs [56]. Data from the Barnes maze test suggested the impaired ability of 5-HT₇ KO mice to utilise hippocampal-dependent allocentric memory [56]. Interestingly, it has been hypothesised that the decrease in the hippocampal expression of 5-HT₇R may underlie age-related deficits in allocentric spatial navigation [57].

The role of 5-HT₇R was also evaluated in the novel object recognition test (NORT). 5-HT₇R KO mice did not differ in their ability to discriminate a novel object from the WT mice [56], whereas SB-269970 exerted no effect or even improved recognition memory when administered before the acquisition trial [56, 58]. On the other hand, SB-269970 was shown to induce a NORT deficit when administered during the consolidation phase in mice [59]. At the same time, the improvement was noted after 5-HT₇R activation. Thus, it seems likely that 5-HT₇R may play a different role in the acquisition and consolidation of recognition memory. Moreover, changes in the expression of 5-HT₇R may underlie novelty-seeking behaviour in rats that in turn also affects their ability to discriminate objects [60, 61].

In an autoshaping Pavlovian/instrumental learning task, AS19 impaired short-term memory (STM) but improved long-term memory (LTM) [62, 63]. Another 5-HT₇ agonist,

LP-211, did not affect STM, but it improved LTM [64], (reviewed in detail by Meneses [65]). The pro-cognitive actions of either AS19 or LP-211 were blocked by the 5-HT₇R antagonist SB-269970. The 5-HT₇R agonists LP-44 and AS19 failed to facilitate emotional memory in the passive avoidance task in mice [50]. However, the lack of effect was ascribed to the low efficacy of LP-44 and AS19 for stimulating protein phosphorylation of 5-HT₇R-activated signalling cascades. Data from our laboratory indicate that AS19 also did not affect rats' performance on the attentional set-shifting task (ASST) [66]. Conversely, SB-269970 (1 mg/kg) enhanced cognitive flexibility on the ASST. Moreover, SB-269970 (1 mg/kg) was demonstrated to improve reference, but not working, memory as assessed in a radial arm maze task [67]. It might be concluded that increasing the task complexity allows for revealing the pro-cognitive effects of 5-HT₇R blockade.

Although the role of 5-HT₇R in modulating cognitive processes under physiological conditions is not fully understood [55, 65, 68, 69], recent reports suggest the efficacy of 5-HT₇R ligands in overcoming cognitive impairments in disease models (described below).

8 Schizophrenia

A possible role for 5-HT₇R s in the pathophysiology of schizophrenia was suggested by post mortem studies that demonstrated marked reductions in the level of 5-HT₇R in the prefrontal cortex of schizophrenia patients [70, 71]. Moreover, a genetic polymorphism study found a positive association between the 5-HT₇R gene and schizophrenia [72].

Thus, 5-HT₇R antagonists have been evaluated in animal models predictive of antipsychotic-like activity, based on the administration of amphetamine or antagonists of *N*-methyl-D aspartic acid (NMDA) receptors. Antagonists of the NMDA receptors, such as phencyclidine (PCP), ketamine or dizocilpine, may evoke not only behaviours reflecting positive symptoms (e.g. hyperactivity) but also negative symptoms (e.g. social withdrawal) and cognitive impairments [73].

The 5-HT₇R antagonist SB-269970 significantly blocked amphetamine-, PCP- and ketamine-induced hyperactivity in rats and mice [58, 74]. Another 5-HT₇R antagonist, SB-258741, also reversed amphetamine-induced hyperactivity but reduced motility of rats at similar doses [75]. Schizophrenic patients also suffer from disturbances in information processing, reflected as a deficient sensorimotor gating, which may contribute to the cognitive deficits that characterise this disorder [76]. Thus, several studies assessed the effects of a 5-HT₇R antagonist on an

operational measure of sensorimotor gating, i.e. prepulse inhibition (PPI) of the startle reflex. Accordingly, SB-269970 did not reverse the deficits in PPI evoked by ketamine in rats [77] and mice [74] or by PCP in rats and mice [78]. On the other hand, SB-269970 blocked the amphetamine-induced PPI deficits in mice [74]. However, 5-HT₇R s may play a partial role in the glutamatergic PPI model, as 5-HT₇R KO mice were less prone to the PCP-induced disruption of PPI than WT mice [78]. In addition, another 5-HT₇R antagonist, SB-258741, normalised PCP-disrupted PPI but was ineffective in the amphetamine-based model [75].

Pro-cognitive effects of 5-HT₇R antagonists in animal models of schizophrenia have been supported by several studies. Specifically, deficits of prefrontal cortex functions, a core feature of schizophrenia, have been ameliorated by the blockade of 5-HT₇R s. Accordingly, SB-269970 attenuated the PCP-induced deficits in reversal learning [79], the dizocilpine-induced impairment in working memory as assessed in a delayed non-matching to position task in rats [80] and ketamine-induced cognitive inflexibility on the ASST in rats in our hands [77]. SB-269970 also reversed memory deficits demonstrated in an autoshaping Pavlovian instrumental learning task in rats after systemic administration of dizocilpine [81] or after an intra-prefrontal infusion of ketamine [82]. The compound was also effective against ketamine- and PCP-induced deficits in the NORT in rats [77, 83]. Moreover, another antagonist of 5-HT₇R s, SB-656104-A, reversed dizocilpine-induced learning and memory impairments in the passive avoidance and Morris water maze tests in rats [84].

The pharmacological blockade of 5-HT₇R s may also have therapeutic implications for the treatment of negative symptoms in schizophrenia. Although SB-25874 had no beneficial effects on PCP-evoked deficits in social interactions [75], SB-269970 ameliorated ketamine-induced social withdrawal in rats [77].

Experimental data suggest the role of 5-HT₇R antagonism in the pro-cognitive actions of the antipsychotic drugs amisulpride and lurasidone. Co-treatment with the 5-HT₇R agonist AS19 reversed the abilities of amisulpride and lurasidone to ameliorate the PCP-induced deficits in the NORT in rats [83] as well as blocked the attenuating effects of lurasidone on the MK-801-induced deficits in the rat passive avoidance test [85]. The amisulpride-induced enhancement of set-shifting ability was also blocked by AS19 [66]. Additionally, the antagonism of 5-HT₇R s may contribute to the mechanisms underlying the pro-social action of amisulpride in rats [86]. It cannot be excluded that the 5-HT₇R may be involved in pro-cognitive effects of other antipsychotic drugs (as for example clozapine) that also possess high affinities for the 5-HT₇R [87].

9 Pain

Several preclinical findings support the utility of 5-HT₇R agonists in treating neuropathic pain. Accordingly, AS19 and E-55888 reversed mechanical hypersensitivity induced by capsaicin in mice, a model predictive of the anti-nociceptive action of analgesics in neuropathic pain [18]. Moreover, activation of 5-HT₇Rs also reduced the nerve injury-evoked mechanical and thermal hyperalgesia in a model of sciatic nerve ligation in mice [88] and rats [89]. This approach may also be effective in treating diabetic neuropathic pain, as AS19 reduced thermal hyperalgesia in streptozotocin-induced experimental diabetes in mice [90].

However, the role for 5-HT₇R in modulation of pain seems to be quite complex (reviewed by Viguiet et al. [91]). Indeed, it has been demonstrated that under sensitising neuropathic conditions, activation of 5-HT₇Rs exerts anti-nociceptive effects at the level of the spinal cord but pro-nociceptive effects in the periphery [92]. However, after systemic administration of 5-HT₇R agonists, the anti-nociceptive effect mediated by central 5-HT₇Rs seems to predominate. Moreover, the effects of 5-HT₇R agonists may be different in neuropathic versus intact healthy animals. For example, AS19 exerted a pro-nociceptive action in healthy rats but alleviated nerve injury-evoked hyperalgesia [91].

10 Epilepsy

The 5-HT₇R has also been linked to seizure activity. The 5-HT₇R antagonist SB-258719 was effective in reducing spontaneous epileptic activity in the WAG/Rij rat model of absence epilepsy [93]. In pilocarpine-induced rat models of temporal lobe epilepsy, the 5-HT₇R antagonist SB-269970 also reduced the number of seizures [94]. The opposite effect was demonstrated by the 5-HT₇R agonist AS19 in that model. In contrast to pharmacological data, a deletion of the 5-HT₇R decreased the electrical and chemical seizure thresholds [95]. In line with these data, the efficacy of 5-CT against convulsions produced by picrotoxin was blocked by SB-269970 [96]. Thus, data appear inconsistent as to whether an activation or blockade of 5-HT₇Rs will produce antiepileptic activity.

11 Other Implications

The ligands of 5-HT₇Rs may also be considered as a possible novel therapeutic target in autism spectrum disorders (discussed in detail by Ciranna and Catania [97]). Key evidence comes from a study demonstrating that 5-HT₇R activation by LP-211 corrected excessive metabotropic

glutamate receptor-mediated LTD in Fmr1KO mice, a model of Fragile X Syndrome also considered as an animal model of autism [98].

Recently, LP-211 was demonstrated to improve Rett Syndrome-related defective performance, including the anxiety-related profile, motor abilities and memory, in a mouse genetic model of the disease [99].

It has also been demonstrated that the activation of 5-HT₇Rs is responsible for serotonin-evoked cranial vasodilatation, which is considered to be one of the mechanisms involved in migraines. Accordingly, the 5-HT₇R antagonist SB-269970 inhibited the 5-CT-induced dilatation in the middle meningeal artery in rats [100]. SB-269970 also reduced neurogenic dural vasodilation evoked by electrical stimulation of dura mater, whereas the 5-HT₇R agonist AS19 increased it [101].

Preclinical studies have demonstrated the involvement of 5-HT₇R in the modulation of impulsivity [102], arousal [46] and novelty-seeking behaviour [60, 61, 103]. Thus, possible links to attention-deficit hyperactivity disorder may also be suggested.

Finally, the involvement of 5-HT₇Rs in processes that contribute to the development and maintenance of addictive behaviours may suggest a potential role for these receptors in alcohol and drug dependence (reviewed in detail by Hauser et al. [104]).

12 Summary

Evidence supports the role for the 5-HT₇R in a wide range of pathological processes. Nevertheless, only one published study has been designed to assess the clinical efficacy of a 5-HT₇R antagonist, JNJ-18038683, in patients with depression [16]. Unfortunately, this clinical trial was reported as a failed study lacking assay sensitivity due to a high placebo response. Some examples of the utility of 5-HT₇R blockade may be clinically effective drugs such as amisulpride, lurasidone or vortioxetine that are characterised by having significant affinity for 5-HT₇R [23, 29, 30].

One may notice the heterogeneous results regarding the effects of both antagonists and agonists of 5-HT₇Rs, which may hamper the clinical validation of the ligands of this receptor. For example 5-HT₇R antagonists exhibit an antidepressant-like activity, but REM sleep suppression may be induced by either agonists or antagonists of those receptors [38]. Moreover, both agonists and antagonists may exert anxiolytic-like effects [25, 46]. Similarly, 5-HT₇R is necessary for hippocampal-dependent functions [55], and the activation of this receptor reversed memory deficits on a hippocampal-dependent task in a mouse model of Rett syndrome [99]. On the other hand, antagonists of

5-HT₇Rs may be beneficial in treating schizophrenia-like cognitive impairments [77, 83]. This may stem from technical reasons like the use of unselective 5-HT agonists or a low efficacy of available compounds, as, for example, AS19 [50]. Moreover, dual agonist/antagonist properties were reported for LP-211 [105]. It has also been suggested that 5-HT₇R-mediated signalling does not fit a two-state activation/blockade model [38]. The role of the 5-HT₇R may depend on the brain region [38] and neurochemical environment (e.g. serotonin level) [69] and may differ between physiological and pathological conditions [91]. Moreover, alternative signalling pathways and homo/heterodimerisations reveal a complex picture of the 5-HT₇R [106, 107]. Of note is also the concept of so called biased agonism or functional selectivity at GPCRs, which implies that different ligands can activate distinct signalling pathways and differentially regulate desensitization, internalization, down-regulation and dimerization processes [108]. It is possible that biased agonism may explain differential effects between different 5-HT₇R antagonists/agonists and even similar effects shared between agonists and antagonists [10, 109]. Thus, further studies are necessary to extend our knowledge of the 5-HT₇Rs and therapeutic potential of their ligands.

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Conflict of interest None declared.

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