



Review

# Multi-Target Directed Ligands (MTDLs) Binding the $\sigma_1$ Receptor as Promising Therapeutics: State of the Art and Perspectives

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**Abstract:** The sigma-1 ( $\sigma_1$ ) receptor is a ‘pluripotent chaperone’ protein mainly expressed at the mitochondria–endoplasmic reticulum membrane interfaces where it interacts with several client proteins. This feature renders the  $\sigma_1$  receptor an ideal target for the development of multifunctional ligands, whose benefits are now recognized because several pathologies are multifactorial. Indeed, the current therapeutic regimens are based on the administration of different classes of drugs in order to counteract the diverse unbalanced physiological pathways associated with the pathology. Thus, the multi-targeted directed ligand (MTDL) approach, with one molecule that exerts poly-pharmacological actions, may be a winning strategy that overcomes the pharmacokinetic issues linked to the administration of diverse drugs. This review aims to point out the progress in the development of MTDLs directed toward  $\sigma_1$  receptors for the treatment of central nervous system (CNS) and cancer diseases, with a focus on the perspectives that are proper for this strategy. The evidence that some drugs in clinical use unintentionally bind the  $\sigma_1$  protein (as off-target) provides a proof of concept of the potential of this strategy, and it strongly supports the promise that the  $\sigma_1$  receptor holds as a target to be hit in the context of MTDLs for the therapy of multifactorial pathologies.

**Keywords:** sigma receptors; sigma-1 receptor; multi-target directed ligands (MTDLs); sigma-1 ligands; polypharmacology



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## 1. Introduction

The most exploited paradigm in medicinal chemistry is the “one-target, one-disease”, according to which ligands are developed to act toward a single target in order to exert a beneficial effect. This kind of approach, even if largely applied, may lead to unsuccessful results. Indeed, pathologies are mostly based on tangled mechanisms that involve different kinds of targets. Thus, a single target approach could be inappropriate because of its impossibility to produce an effect on the different pathways associated with the pathology.

On the basis of this idea, a multi-target strategy has been proposed in order to hit at the same time the diverse targets involved and modulate the diverse mechanisms that underlie the pathology.

The first step of this multi-target strategy has been the co-administration of more drugs all together, with the aim of obtaining a synergic effect. Some examples of this approach are represented by current therapeutic programs. Pathologies such as hypertension, cancer, neurodegeneration, AIDS, and depression can require the administration of up to three different classes of drugs.

Although this approach has therapeutic beneficial effects, the higher the number of drugs administered, the higher the number of metabolites that could produce side effects. Moreover, the co-administration of different drugs can produce cross-resistance to the

therapeutics and inconvenient pharmacokinetic profiles. With the aim to overcome such problems, the multi-target directed ligand (MTDL) approach has been introduced. This strategy is based on the administration of a single drug with multiple effects because such a drug incorporates two or more pharmacophores in a single molecule. This incorporation can produce *hybrid drugs* or *chimeric drugs*. *Hybrid drugs* are obtained when two or more pharmacophores are connected using a stable or metabolizable linker. These structures not only have a high molecular weight, which is detrimental for oral bioavailability, but they are also very flexible, so that binding to the targets can be reduced. On the other hand, *chimeric drugs* are obtained by fusing or merging two or more different pharmacophores into one. In contrast to the former type, *chimeric drugs* have better pharmacokinetic properties and better interaction with targets because of their rigidity [1,2].

The synthesis of MTDLs can follow a *knowledge-based approach* or a *screening approach*. The former approach is based on the use of diverse and focused libraries of molecules and relies on well-known drugs and compounds. In the *screening approach* instead, ligands that demonstrate a solid affinity for a certain target are explored in their activities/affinities for other targets. However, in both cases, a fine work of optimization is needed to obtain the best compromise that guarantees the interaction with all targets [3].

In this review, the authors want to discuss the use of the MTDL approach that exploits the interaction with sigma ( $\sigma$ ) receptors. In fact, even if these receptors are still not completely understood, their involvement in several pathologies has been widely demonstrated, so that the synergy obtained by a simultaneous interaction with  $\sigma$  receptors and other biological targets appears as a beneficial strategy to face multifactorial pathologies.

$\sigma$  Receptors were discovered in 1976, when studies performed on opioid receptors revealed the presence of proteins that do not bind **naloxone** and **etorphine** but display high affinity for **(+)-pentazocine**, which is still used in binding studies [4]. A milestone in the history of  $\sigma$  receptors has been attained when two different protein subtypes were discovered, namely  $\sigma_1$  and  $\sigma_2$  receptors [5].

## 2. $\sigma_1$ Receptors

$\sigma_1$  Receptors have been found in the central nervous system (CNS), particularly in the granular layer of the olfactory bulb, in many cortical layers, and in the dentate gyrus [6], where they exert their most important activities. A slightly lower expression has been also found in some pyramidal layers of the hippocampus, various hypothalamic nuclei, the septum, the central gray, the motor nuclei of the hindbrain, and the dorsal horn of the spinal cord [6]. At the cellular level,  $\sigma_1$  receptors have been found in ependymocytes, which border the ventricular compartments, and in neurons located within the CNS parenchyma [6].

In peripheral organs,  $\sigma_1$  receptors have been found in the gastrointestinal tract [7], vas deferens [8], in liver and kidney [9], heart [10], adrenal medulla, pituitary, testis, and ovaries [11].

The  $\sigma_1$  receptor is localized at the mitochondrial-associated endoplasmic reticulum (ER) membranes (MAM) in association with the binding immunoglobulin protein (BiP) in a resting state. Upon agonist stimulation, or  $\text{Ca}^{2+}$  depletion, the  $\sigma_1$  receptor dissociates from BiP and stabilizes inositol 1,4,5-trisphosphate receptor type 3 (IP3R3) at MAM, increasing  $\text{Ca}^{2+}$  transfer from ER into mitochondria where adenosine triphosphate (ATP) production is facilitated [12]. Recently, it has been proposed that  $\sigma_1$  receptors affect store-operated  $\text{Ca}^{2+}$  Entry (SOCE), with agonists, such as **(+)-pentazocine**, increasing the SOCE activity [13].

The  $\sigma_1$  subtype is also able to protect against ER stress associated with reactive oxygen species (ROS), which can easily activate the inositol-requiring enzyme 1 (IRE1) at MAM. In this context, the  $\sigma_1$  receptor stabilizes IRE1 and enhances cellular survival, prolonging the activation of the IRE1–XBP1 signaling pathway [14]. Moreover, the interaction of  $\sigma_1$  with B-cell lymphoma 2 (Bcl-2) or nuclear factor erythroid 2-related factor 2 (Nrf2) pathways is able to protect against apoptosis [15]. It is now clear that the  $\sigma_1$  receptor, which is defined as a ‘pluripotent chaperone’ [16], interacts with a number of proteins, as recently

reviewed by Schmidt and colleagues [17], although more evidence is required to ascertain a functional interaction.

This pluripotent nature of the  $\sigma_1$  receptor is responsible for a series of complex effects with the cell state, such as stress conditions, which can produce modifications in the  $\sigma_1$ -mediated response to stimuli. As recently reviewed, it is likely through these protein–protein interactions that the  $\sigma_1$  receptor exerts its action in viral infections and also against SARS-CoV-2 [18]. It has been demonstrated that the  $\sigma_1$  receptor interacts with the NSP6 viral protein, and its knock-out (KO) and knock-down (KD) abate the cells' infection by both SARS-CoV-1 and 2, prompting focused research in this direction. By contrast, the KO and KD of the  $\sigma_2$  subtype, which interact with the viral protein ORF9c, do not impact on cells' infection [19].

The neuroprotective action of  $\sigma_1$  receptor agonists is well established, and it has been proved that this activity is exerted through different mechanisms such as intracellular  $\text{Ca}^{2+}$  regulation, the prevention of oxidative stress, and anti-apoptotic effects. The  $\sigma_1$  subtype contributes to protein homeostasis: it can stimulate neurotrophin receptor signaling and reduce protein aggregation responsible for neurodegenerative disease, and it can also activate autophagy as a protective mechanism against damage arisen by misfolded proteins. Recently, many studies proved the ability of  $\sigma_1$  receptors to directly or indirectly interact with receptors or enzymes with key roles in neurodegeneration, particularly in Alzheimer's disease (AD). Importantly, in patients with AD, a reduction of  $\sigma_1$  receptor density [20] has been demonstrated. Some studies attributed such reduction to the E4 variant of the apolipoprotein E gene (APOE 4) [21], although some controversies still exist [22]. All these mechanisms can promote cell survival and consolidate the role of the  $\sigma_1$  receptor as a target for therapies against neurodegeneration [23].

From a structural point of view, the  $\sigma_1$  protein has a 223 amino acid sequence, conserved among vertebrates, but devoid of similarity with any other protein. The closest protein seems to be ERG2p, which is a C8-C7 sterol isomerase expressed in the yeast. The two proteins share the same steroid binding domain-like (SBDL) regions, although no isomerase activity has been shown for the  $\sigma_1$  receptor [24]. A breakthrough milestone in the  $\sigma_1$  receptor-related research is the crystal structure of the protein, which was published in 2016 [25]. Later, also the crystal structures of the  $\sigma_1$  protein with agonists and antagonists bound to it were disclosed [26], and important insights into the binding modes of the  $\sigma_1$  ligands were provided with evidence for the so far ligands-based generated models. The most important interaction between ligands and the receptor is represented by an electrostatic bond between a basic amine (present in all the high-affinity  $\sigma_1$  ligands) and Glu172, while the rest of the ligand is accommodated in two different hydrophobic areas, which is in line with Glennon's pharmacophore model [27].

According to this model, the  $\sigma_1$  receptor pharmacophore consists of a basic amine site tolerating a little substituent (which could be H or small alkyl groups) and two hydrophobic regions: the *Primary Hydrophobic Region* is 6–10 Å far from the amine site, while the *Secondary Hydrophobic* one is 2.5–3.9 Å far from the amine. Such a model very well fits into the crystal structure, whose availability has rationalized the binding of several molecules to  $\sigma_1$  receptors [28].

Importantly, crystallization revealed a trimeric complex, suggesting that the protein acts through polymerization states. Each subunit is formed by a single transmembrane domain (TMD) and a large cytosolic region that contains the binding pocket for each monomer. The 223 amino acid sequence is organized into five  $\alpha$ -helices and ten  $\beta$ -strands: the *N*-terminus passes through the membrane, forms the only TMD, and protrudes in the ER lumen. The *C*-terminus is a flat hydrophobic sequence associated with the cytosolic surface of the ER. Within the binding pocket, besides the ionic interaction with Glu172,  $\sigma_1$  receptor ligands interact with Tyr103 (through hydrogen bonds with hydrophilic residues), which provides a favorable environment for the hydrophobic bonds within the primary hydrophobic region (formed by Val84, Ala86, Trp89, Met93, Leu95, Ala98, Tyr103, Leu105, Phe107, Tyr120, Ile124, Trp164, Met170, Ile178, Thr181, Leu182, Phe184, Ala185, Thr202, and

Tyr206). The secondary hydrophobic region (made of Trp89, Ser117, Tyr120, Ile124, Asp126, Phe133, Val152, His154, Thr160, Val162, Trp164, and Met170, with Ser117 and His154 exhibiting their hydrophobic side chain to the cavity) tolerates smaller groups compared to the primary one [27,28]. Interestingly, the crystal structure of the receptor bound to its ligands revealed how the agonists, in contrast to the antagonists, induce a structural shift of the  $\alpha$  4 helix, likely preventing the oligomerization state, supporting that the action of the  $\sigma_1$  receptor occurs through protein–protein interaction (PPI). Therefore, while  $\sigma_1$  ligands may function as allosteric modulators of PPIs, the different oligomeric structures could be responsible for the many activities performed by these versatile receptors, with agonists and antagonists differently influencing the association among protomers: agonists produce lower oligomeric structures such as monomers and dimers, while antagonists produce higher ones [29].

#### *Overview on $\sigma_1$ Receptors Ligands: Functional Activity, Proposed Endogenous Ligands, and Reference Compounds*

*Functional activity.* Although the terms *agonist* and *antagonist* have been used to classify  $\sigma_1$  receptor ligands, an unambiguous definition of the functional activity (agonist versus antagonist) is often hard. As a matter of fact, both agonists (i.e., **fluvoxamine** and other selective serotonin reuptake inhibitors (SSRIs) [30]) and antagonists (i.e., **rimcazole** [31,32]) are effective in treating some pathologies such as psychosis, and there are some ligands (i.e., **BMY 14802** [33,34]) that show both agonist and antagonist activities in different conditions [35].

With the aim to unequivocally ascertain agonist vs. antagonist activity, many studies have been carried out. Among them, an interesting approach was developed by Gomez-Soler and colleagues, who developed a biosensor exploiting the Fluorescence Resonance Energy Transfer (FRET) technique in living cells. The model was based on the genetic decoration of the  $\sigma_1$  receptor with cyan and yellow fluorescent proteins. The distance between these two portions depends on the receptor conformation, which is influenced by the nature of the ligand. In fact, while agonists make the two fluorescent portions more distant, antagonists produce a conformational change that makes the portions closer, resulting in a fluorescence emission due to the energy transfer between them [36]. Therefore, the claimed  $\sigma_1$  receptor agonists and antagonists studied produced decreased and increased FRET signals, respectively. Another step in the same direction was taken by Yano et al., who produced a novel receptor homomer assay based on the Bioluminescence Resonance Energy Transfer (BRET) technique. The  $\sigma_1$  receptor was fused in its C-terminal and N-terminal sites with NanoLuciferase (NL) (BRET donor) and the yellow fluorescent protein Venus (VN), which works as an acceptor. The most suitable fusion construct pairs were identified to evaluate the ligand-induced BRET signal, and antagonists were shown to promote higher-order homomerization [35], with results from this assay in agreement with biochemical assays. The same BRET approach was also used to evaluate the heteromerization between the  $\sigma_1$  receptor and BiP, with the former protein bearing NL and the latter bearing the VN portions. Again, **haloperidol** and **(+)-pentazocine** displayed an opposite trend. Nevertheless, the same authors did not use the definition ‘agonist’ or ‘antagonist’ but preferred to discuss the phenotypes of the studied molecules, as some unexpected discrepancies emerged in the ligands studied (e.g., NE100, cocaine). All in all, even if a clear distinction between the two classes is still missing, these fluorescent-based assays provide useful information about the conformational changes that underlie  $\sigma_1$  receptors’ mechanisms of action.

*Proposed endogenous ligands.* The  $\sigma_1$  protein has been considered an orphan receptor for a long time because of the lack of an endogenous ligand. Nevertheless, some years ago, the endogenous hallucinogen compound *N,N*-dimethyltryptamine (**DMT**) showed to protect  $\sigma_1$  receptors by photolabeling performed using two radioactive photoaffinity labels: 3-[<sup>125</sup>I]iodo-4-azidococaine ([<sup>125</sup>I]-IACoc), more specific for  $\sigma_1$  receptors and 1-*N*-(2',6'-dimethyl-morpholino)-3-(4-azido-3-[<sup>125</sup>I]iodo-phenyl)propane ([<sup>125</sup>I]IAF), with affinity for both  $\sigma$  receptor subtypes. **DMT** provided a dose-dependent protection when



either [<sup>125</sup>I]-IACoc or [<sup>125</sup>I]IAF was used. Moreover, **DMT** showed to inhibit voltage-gated Na<sup>+</sup> ion channels in both native cardiac myocytes and heterologous cells that express  $\sigma_1$  receptors. This pharmacological profile suggested **DMT** as an endogenous agonist for the  $\sigma_1$  receptor ( $K_d = 14.75 \mu\text{M}$ ) [37]. In addition to **DMT**, **Progesterone**, which binds both  $\sigma$  subtypes ( $\sigma_1 K_i = 239 \text{ nM}$ ,  $\sigma_2 K_i = 441 \text{ nM}$  [38]), has been also proposed as an endogenous  $\sigma_1$  receptor antagonist able to coordinate endocrine, immune, and CNS [38,39]. This is not surprising if we consider that  $\sigma_1$  receptors share homology with yeast sterol isomerase [24]. However, these ligands display low  $\sigma_1$  receptor affinity, and their blood concentration is too low for these ligands to be considered endogenously active. Plenty of other ligands can bind  $\sigma_1$  receptors with high affinity. Molecular dynamic simulations at the  $\sigma_1$  receptor binding pocket have shown how the diverse chemical structures to which high-affinity  $\sigma_1$  receptor ligands belong may easily be accommodated producing different associations among protomers that lead to the different activities observed.

Reference compounds. The most important classes of ligands are briefly summarized below (Table 1):

*(+)-Benzomorphans as agonists:* This class of ligands has a great historical value, as (+)-*N*-allylnormetazocine ((+)-**SKF-10047**) led to distinguishing a new group of receptors different from opioid receptors [40] that were named  $\sigma$ , after the first letter of the compound code [41]. Moreover, (+)-**Pentazocine** is still a  $\sigma_1$  reference compound, and its tritium radiolabeled form, which shed light on the existence of two classes of  $\sigma$  receptors [4], is still used for  $\sigma_1$  receptor radioligand binding assays.

*Antipsychotics as antagonists:* **Haloperidol** has high affinity for  $\sigma_1$  receptors ( $\sigma_1 K_i = 8 \text{ nM}$  [9]), but the involvement of the  $\sigma_1$  protein in schizophrenia has not completely been demonstrated. Several investigations on  $\sigma_1$  receptor gene polymorphs in this context are underway [42,43].

*Antidepressants as agonists:* **Imipramine**, **Fluoxetine**, **Fluvoxamine**, and **Sertraline** showed moderate to high affinities for  $\sigma_1$  receptors ( $K_i$  values ranging from 30 to 300 nM) [44], and several  $\sigma_1$  receptor agonists have shown antidepressant-like effects in animal models of depression, proving the involvement of the protein in depression [45,46].

*Neurosteroids as agonists/antagonists:* This class contains both agonists and antagonists. **Progesterone** in fact is a  $\sigma_1$  receptor antagonist, while **deoxycorticosterone**, **testosterone**, **pregnenolone-sulfate**, and **dehydroepiandrosterone (DHEA)** can produce agonist activities. All these ligands have unconventional structures because of the absence of a basic nitrogen that determines weak affinities for  $\sigma_1$  receptors. Neurosteroids have been proposed as endogenous ligands for  $\sigma_1$  receptors, as their effect seems also to be mediated by  $\sigma_1$  receptor binding [39,47].

*Others:* A number of other ligands have been synthesized with the aim to better understand the role of these receptors in different pathologies. The most representative examples are as follows:

- **SA4503:** a highly selective agonist proved to exert effects on memory, depression, cardiac hypertrophy, and hearing [48–52];
- **PB190:** a selective agonist that showed neuroprotective and antidepressant activities [53–55];
- **PRE-084:** a selective agonist with beneficial effects on learning impairment [56–58];
- **NE-100:** a  $\sigma_1$  reference antagonist often used to counteract the action of claimed  $\sigma_1$  agonists [59,60];
- **PB212:** a subnanomolar affinity and selective  $\sigma_1$  antagonist [53,61];
- **AC915:** a highly selective ligand with an antagonist profile [62];
- **Pridopidine:** initially considered a dopaminergic D<sub>2</sub> receptor antagonist, it was later repositioned as a selective  $\sigma_1$  receptor agonist (see Section 3.5) [63];
- **FTC-146:** the ligand with the highest affinity and selectivity for  $\sigma_1$  receptor. It has been radiofluorinated and employed in Positron Emission Tomography (PET) in mice, rats, squirrels, monkeys, and humans [64–66];

- **S1RA**: a  $\sigma_1$  receptor antagonist developed by Esteve company for the treatment of neuropathic pain and the strengthening of opioid analgesia, which successfully completed Phase I clinical trial showing safety and tolerability [67,68];
- **BD1063**: a  $\sigma_1$  receptor antagonist with anti-cocaine effects in mice [69,70].

**Table 1.** Representative  $\sigma_1$  receptor ( $\sigma_1$  R) ligands and their affinities for  $\sigma_1$  R and  $\sigma_2$  receptor ( $\sigma_2$  R).

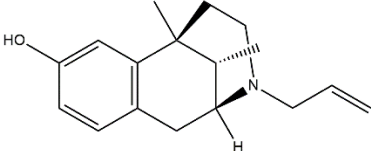
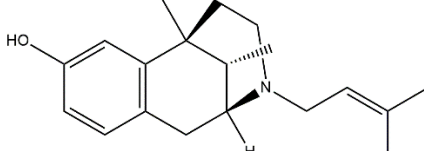
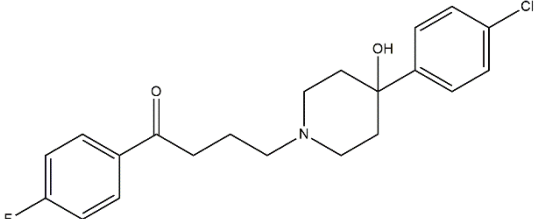
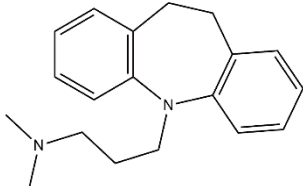
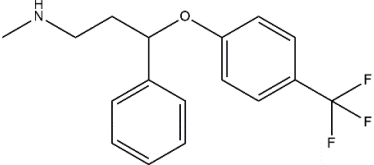
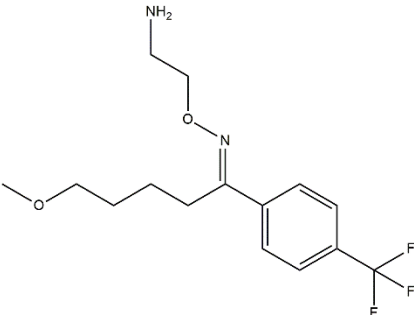
Name	Structure	$\sigma_1$ R $K_i$ nM	$\sigma_2$ R $K_i$ nM	Reference for Binding Values
<b>(+)-Benzomorphans:</b>				
(+)-SKF-10047		153	154335	[9]
(+)-pentazocine		15.4	3475	[9]
<b>Antipsychotics:</b>				
Haloperidol		1.09	41.9	( $\sigma_1$ R) [71] ( $\sigma_2$ R) [9]
<b>Antidepressants:</b>				
Imipramine		343	2107	[44]
Fluoxetine		240	16100	[44]
Fluvoxamine		36	8439	[44]

Table 1. Cont.

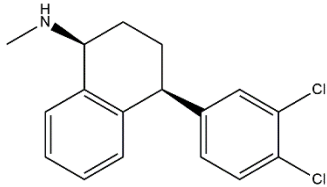
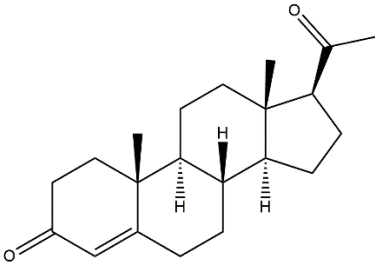
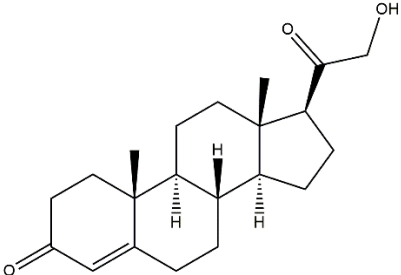
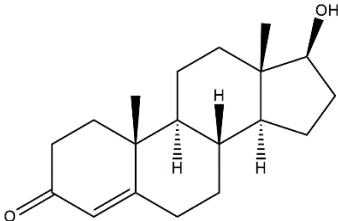
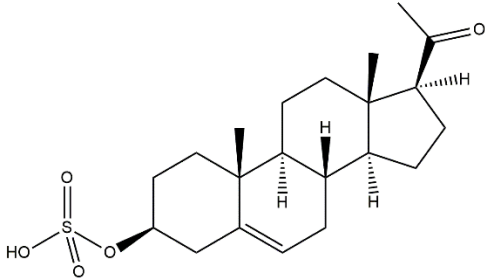
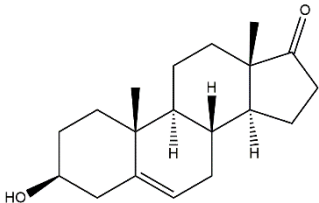
Name	Structure	$\sigma_1$ R $K_i$ nM	$\sigma_2$ R $K_i$ nM	Reference for Binding Values
Sertraline		57	5297	[44]
<b>Neurosteroids:</b>				
Progesterone		239	441	[38]
Deoxycorticosterone		938	n.d.	[39]
Testosterone		1014	n.d.	[39]
Pregnenolone-sulphate		3196	n.d.	[39]
DHEA		2.959	n.d.	[47]

Table 1. Cont.

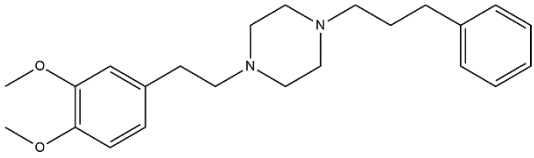
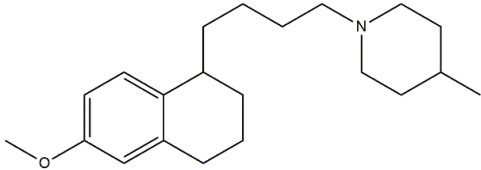
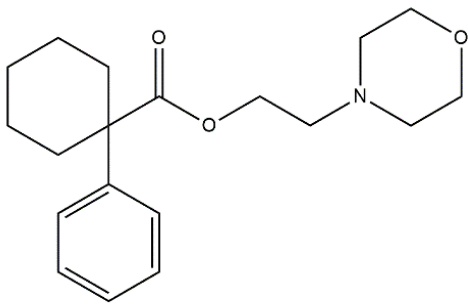
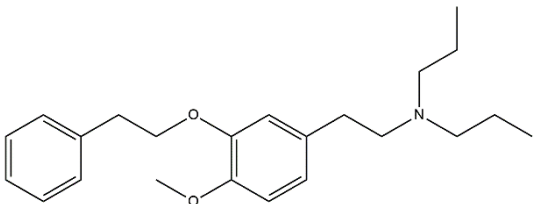
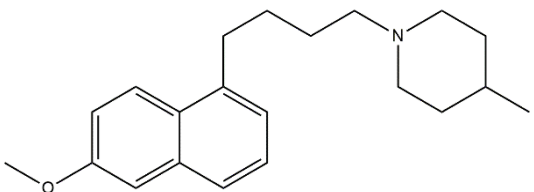
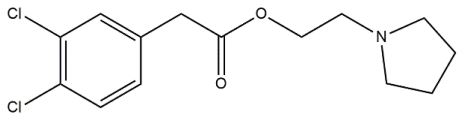
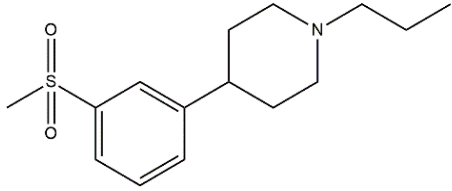
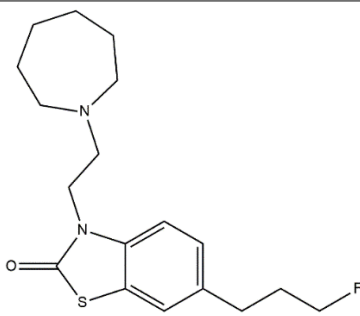
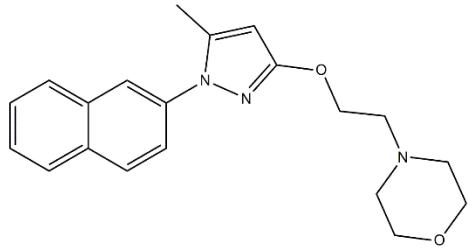
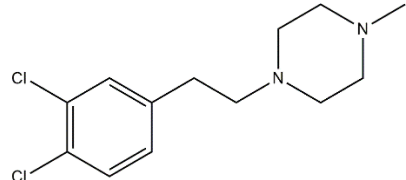
Name	Structure	$\sigma_1$ R $K_i$ nM	$\sigma_2$ R $K_i$ nM	Reference for Binding Values
<b>Others:</b>				
SA4503		4.63	63.09	[72]
PB190		0.42	36.3	[53]
PRE-084		53.2	32.100	[73]
NE-100		1.1	170	[74]
PB212		0.030	17.9	[53]
AC915		4.89	>10000	[62]
Pridopidine		57	5450	[75]

Table 1. Cont.

Name	Structure	$\sigma_1$ R $K_i$ nM	$\sigma_2$ R $K_i$ nM	Reference for Binding Values
FTC-146		0.0025	364	[64]
S1RA		23.5	>1000	[76]
BD1063		9.15	449	[70]

### 3. $\sigma_1$ Receptor Ligands in a MTDLs Approach

In addition to the direct neuroprotective action of  $\sigma_1$  receptors, the additional modulation of targets such as opioid, N-methyl-D-aspartate (NMDA), dopaminergic, and cholinergic receptors renders the  $\sigma_1$  protein an intriguing target for the modulation of processes that involve these systems, prompting the development of  $\sigma_1$ -based MTDLs for the treatment of complex and multifactorial pathologies such as AD.

#### 3.1. MTDLs Acting at $\sigma_1$ Receptor and Cholinergic System

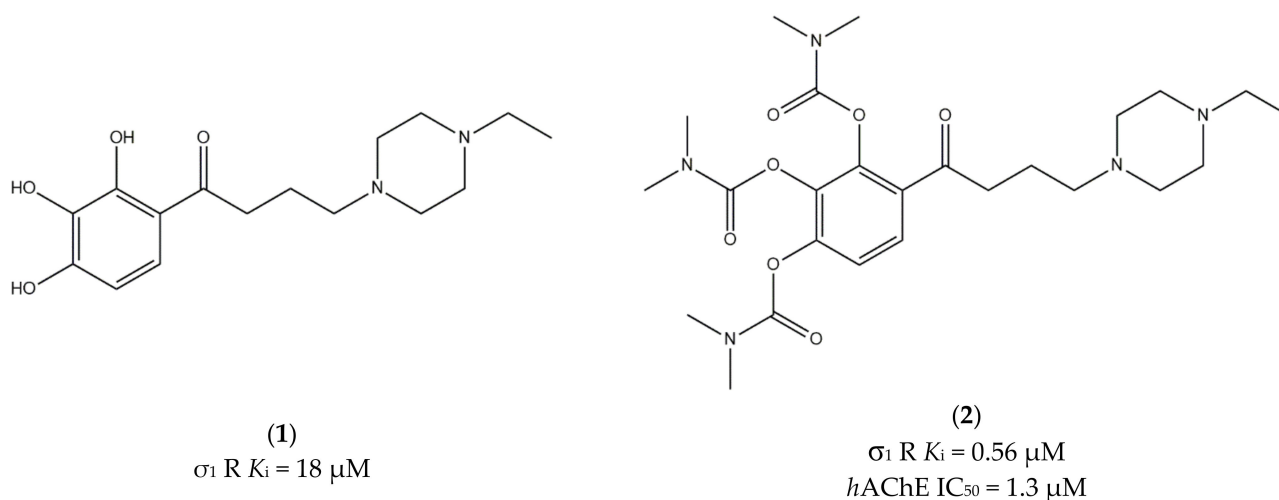
Drug metabolism leads to metabolites that can be more potent or less potent than the parent drug. In the former case, the drug can be considered a sort of prodrug. Thus, the simultaneous presence of the two chemical entities may produce a synergistic powerful effect.

Starting from this idea, in 2010, Lecanu et al. developed pairs of drugs and the corresponding prodrugs, which act on different targets such as acetylcholinesterase (AChE) whose inhibition is a consolidated therapeutic strategy in AD, and  $\sigma_1$  receptors. With this aim, two series of molecules were built: hydroxyphenyl-butan-1-ones (drug) and their corresponding carbamates (prodrugs). Upon inhibition of the AChE, the prodrug releases the drug. Thus, the prodrug and drug bind and act through the  $\sigma_1$  receptor and AChE, while the drug exerts its antioxidant action.

Among the studied ligands, two compounds (i.e., 2,3,4-trihydroxy-phenyl)butan-1-one **1** and the corresponding *N,N*-dimethylcarbamoyloxy prodrug **2**; Figure 1) showed the best compromise in terms of activity on the different targets. Compound **2** was able to (i) inhibit AChE with a potency comparable to reference compounds; (ii) bind  $\sigma_1$  receptors (high selectivity, sub-micromolar affinity, and antagonist activity); and (iii) prevent mitochondrial toxicity by inhibiting mitochondrial complex IV and V. On the other hand, compound **1**, even if much less active than its bio-precursor toward  $\sigma_1$  receptors, was also able to



attenuate reactive oxygen species (ROS),  $A\beta_{1-42}$ -induced neurotoxicity, and mitochondrial toxicity by inhibiting complexes I, II, IV, and V.

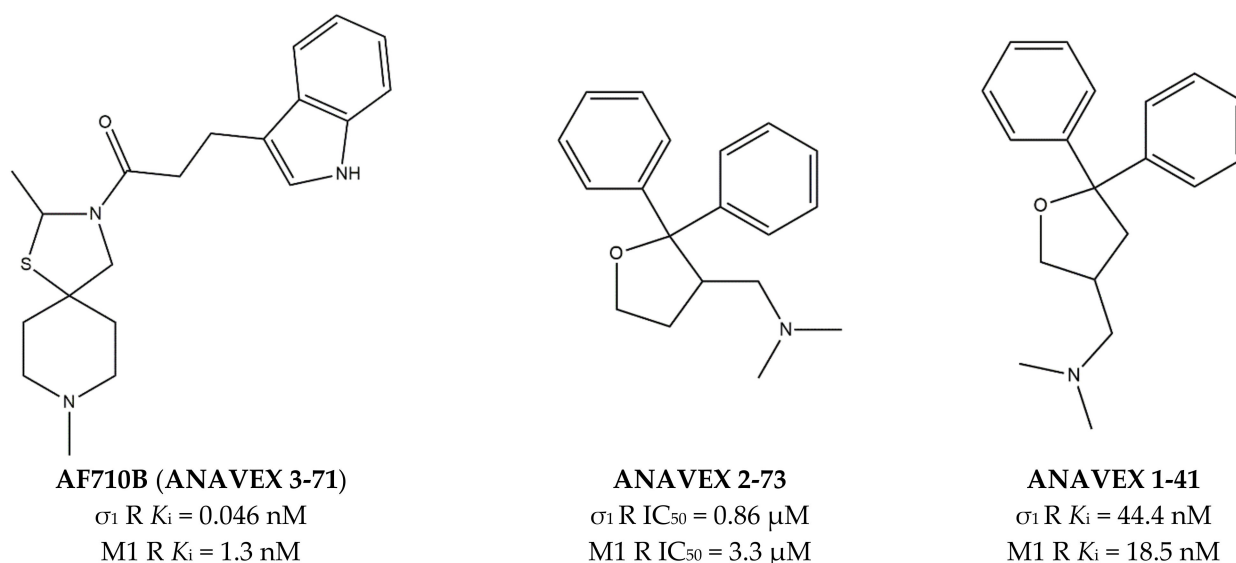


**Figure 1.** Compound (1) and (2) and their  $K_i$  and  $IC_{50}$  values for  $\sigma_1$  receptor ( $\sigma_1 R$ ) and human acetylcholinesterase ( $hAChE$ ) [77].

Moreover, **2** was demonstrated to cross the blood–brain barrier (BBB) very shortly after its administration and be transformed into **1** very quickly.

Behavioral studies on animal models are needed, but preliminary data suggest that this multi-target profile can represent a novel therapeutic strategy to treat AD [77].

Many pharmacological and genetic data have proven that activation of muscarinic M1 receptors (mAChRs) attenuates symptoms of neurodegenerative pathologies [78,79], as in the case of MTDLs able to bind both M1 and  $\sigma_1$  receptors. The most investigated compound representative of this class is **ANAVEX 2-73** (also known as **Blarcamesine**) (Figure 2). This compound is in advanced clinical phases for several CNS diseases such as AD, Parkinson’s disease (PD), Rett, and Fragile X Syndromes (anavex.com/#!/pipeline, accessed Apr 3, 2021). In addition to binding M1 and  $\sigma_1$  receptors, **Blarcamesine** also binds M2–M4 receptors (with micromolar affinity),  $Na^+$  channel site 2, and NMDA receptor (NMDAR) [80,81]. In this context, Fisher and co-workers, who previously developed orthosteric M1 receptors agonists (e.g., **AF102B**, **AF267B**, and **AF292**), extended their approach in order to target also  $\sigma_1$  receptors. With this aim, compound **AF710B** (also known as **ANAVEX 3-71**, Figure 2) that can activate both M1 and  $\sigma_1$  receptors with high potency and selectivity was identified [66]. **AF710B** is a positive allosteric modulator (PAM) of M1 receptor, as it improves the efficacy of carbachol, and this activity, together with a comparable agonism at the  $\sigma_1$  receptor can preserve synaptic elements in vitro. In vivo studies performed on trihexyphenidyl-treated rats and 3xTg-AD mice showed that **AF710B** can restore cognitive deficits and attenuate signs of AD phenotypes by the reduction of  $\beta$ -secretase 1 (BACE1) levels, GSK3 $\beta$  and CDK5/p25 activity (which contribute to the hyperphosphorylation of tau protein), neuroinflammation, soluble and insoluble  $A\beta_{40}$  and  $A\beta_{42}$  plaques, and tau pathology [82]. In fact, **AF710B** reduces the expression of the putative BACE1, so that proteolytic fragments produced by  $\beta$ -secretase were considerably lower in 3xTg-AD treated than in untreated mice. Moreover, tau kinases GSK3 $\beta$  and CDK5 take part in the mechanism of hyperphosphorylation of tau protein. In particular, in AD patients, CDK5 activator p35 is cleaved to produce the protein p25, which binds with high affinity and activates GSK3 $\beta$  [83]. The activation of M1 receptors produces a reduction of GSK3 $\beta$  expression, while the activation of  $\sigma_1$  prevents the formation of CDK5/p25. Therefore, the inhibition of GSK3 $\beta$  and CDK/p25 by **AF710B**, upon interaction with both M1 and  $\sigma_1$  receptors, results as a promising approach in the treatment of tauopathies [82].



**Figure 2.** ANAVEX 3-71, 2-73 and 1-41 structures and their  $K_i$  and  $IC_{50}$  values for  $\sigma_1$  receptor ( $\sigma_1$  R) and muscarinic M1 receptor (M1 R) [82,84,85].

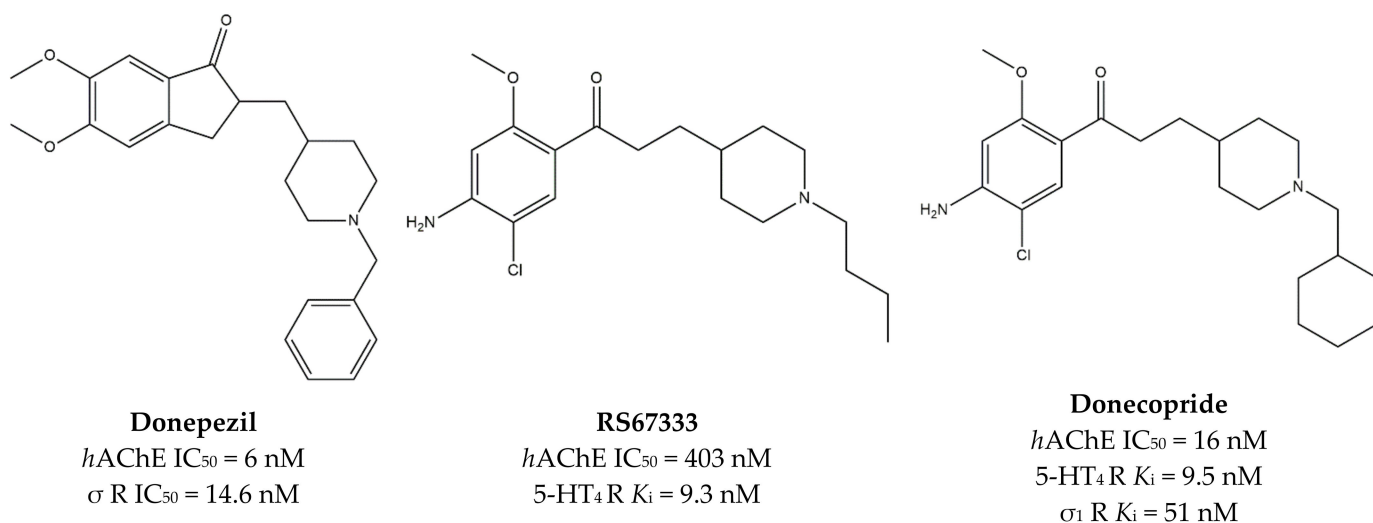
The effect of  $\sigma_1$  receptors in inflammation through microglia modulation has been reported [54,86,87], and **AF710B** was shown to reduce reactive astrocytes and activated microglia in the animals, as detected by the low levels of glial fibrillary acidic protein (GFAP) and ionized calcium-binding adapter molecule 1 (Iba-1). Notably, astrocytes and microglia are increased in number and size in AD patients.

Another study performed using **AF710B** on McGill-R-Thyl-APP transgenic (tg) rats revealed that this MTDL can reduce amyloid pathology and markers of neuroinflammation while increasing amyloid cerebrospinal fluid clearance and synaptic marker. The most important achievement is represented by the prolonged duration of these effects, which are maintained five weeks after the treatment is interrupted [88].

In addition to **AF710B** and **ANAVEX 2-73**, Anavex Life Sciences Corp portfolio comprehends an isomer of **ANAVEX 2-73**, named **ANAVEX 1-41** (Figure 2) that next to the activity toward  $\sigma_1$  and M1 receptors, also displays activity for  $\alpha_1$ , 5-HT<sub>2</sub>, and D<sub>3</sub> receptors [81], with an indication for the treatment of depression, stroke, and neurodegenerative diseases (anavex.com/#!/pipeline).

### 3.2. MTDLs Acting at $\sigma_1$ , 5-HT<sub>4</sub> Receptors and AChE

In 2015, Rochais and co-workers developed the MTDL **Donecopride** from the combination of the AChE inhibitor **Donepezil** and the serotonergic 5-HT<sub>4</sub> receptor (5-HT<sub>4</sub>R) agonist **RS67333** (Figure 3). Indeed, **Donecopride** inhibits AChE and exerts a partial 5-HT<sub>4</sub>R agonist activity on 5-HT<sub>4</sub>R.



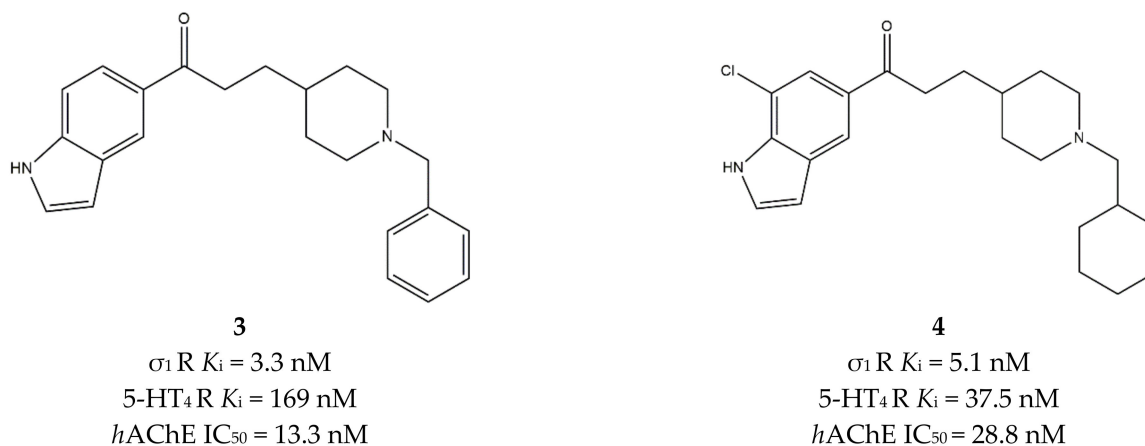
**Figure 3.** Donepezil, RS67333, and Donecopride structures and their K<sub>i</sub> and IC<sub>50</sub> values for  $\sigma$  receptors ( $\sigma$  R),  $\sigma_1$  receptor ( $\sigma_1$  R), human acetylcholinesterase (*hAChE*) and serotonergic 5-HT<sub>4</sub> receptor (5-HT<sub>4</sub> R) [89–91].

Subsequent studies revealed that **Donecopride** has high  $\sigma_1$  receptor affinity (K<sub>i</sub> = 51 nM [90]), which is in agreement with the nanomolar affinity of **Donepezil** for the same target [91].

This finding inspired many studies about the possible therapeutic exploitation of such combinations of activities [92–95]. Starting from these pieces of evidence, Lalut et al. postulated that the replacement of the benzene ring by an indole group, together with the insertion of a piperidine-chained spacer, could improve affinity for the  $\sigma_1$  receptor. Thus, *N*-substituted and *N*-unsubstituted indoles were developed, with diverse decoration on the indole and piperidine rings.

The *N*-unsubstituted indoles displayed a profile comparable to their lead compound in terms of affinity at 5-HT<sub>4</sub> receptors and inhibitory activity at AChE. The most promising ligands were tested *in vitro* on Jukart cell membranes for the determination of the  $\sigma_1$  affinity, according to Ganapathy [96].

The *N*-benzyl derivative **3** (Figure 4) displayed the highest affinity for the  $\sigma_1$  receptor and the most potent inhibition toward AChE but a moderate affinity for 5-HT<sub>4</sub> receptors. The best compromise among affinities at  $\sigma_1$  and 5-HT<sub>4</sub> receptors and activity at AChE was reached by the cyclohexylmethyl derivative **4** (Figure 4), which was thus considered the lead compound of the study.



**Figure 4.** Compounds (**3**) and (**4**) structures and their K<sub>i</sub> and IC<sub>50</sub> values  $\sigma_1$  receptor ( $\sigma_1$  R), serotonergic 5-HT<sub>4</sub> receptor (5-HT<sub>4</sub> R) and human acetylcholinesterase (*hAChE*) [90].

This compound was tested *in vivo* using the dizocilpine-induced amnesia assay in mice. In the 0.1–1 mg/kg dose-range, **4** did not attenuate the dizocilpine-induced spontaneous alternation performance deficit, while at lower doses, the passive avoidance deficit was attenuated with a 40% protection. The authors concluded that the involvement of the  $\sigma_1$  receptor needed further explorations by including challenges with the  $\sigma_1$  receptor antagonist NE-100 [90].

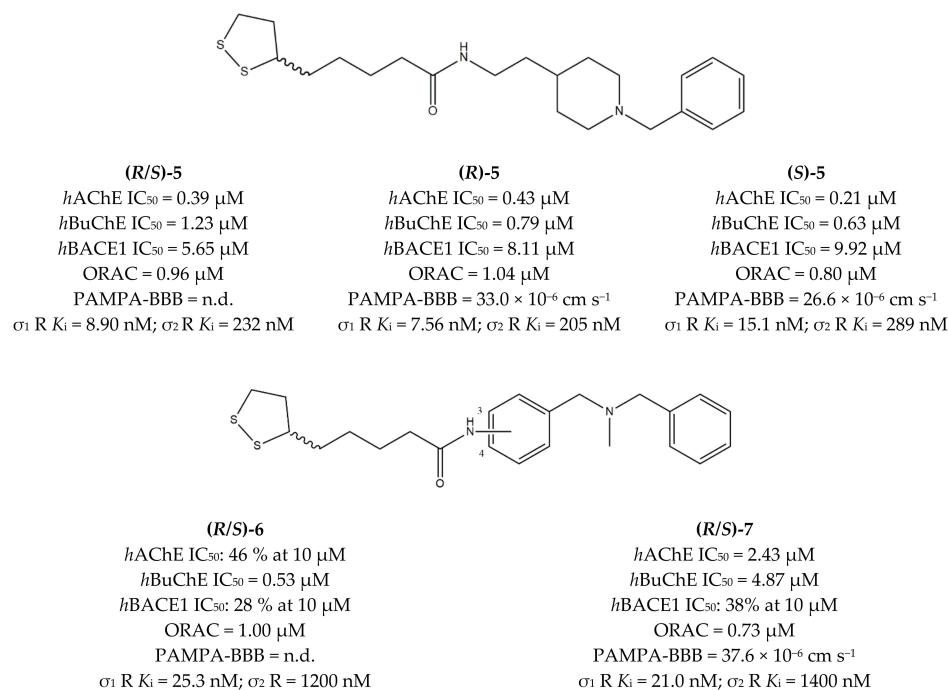
### 3.3. MTDLs Acting at $\sigma_1$ Receptor, AChE, BuChE, BACE1, MAO-A, MAO-B, 5-LOX, ROS, and Stem Cells

Another important class of MTDLs able to treat AD is represented by ligands developed by Estrada and co-workers in 2016. Their strategy was based on the synthesis of MTDLs able to inhibit AChE/Butyrylcholinesterase (BuChE), BACE1, and bind  $\sigma_1$  receptors.

For the study, the authors combined lipoic acid (LA), whose antioxidant properties [97] are exploited in AD [98], together with either the *N*-benzylpiperidine (NBP) moiety (featured by **Donepezil**, as discussed above) or the *N,N*-dibenzyl-*N*-methylamine (DBMA) moiety of the BACE1 inhibitor **AP2238**. This approach led to the MTDLs LA-NBPs and LA-DBMA, respectively.

More than fourteen ligands were developed, and some of them were tested for  $\sigma$  receptors affinity.  $K_i$  values in the sub-micromolar and sub-nanomolar range were found for  $\sigma_1$  receptors, and radical scavenging properties were evaluated using the Oxygen Radical Absorbance Capacity (ORAC) assay, with LA-based ligands showing good antioxidant capacities, comparable to vitamin E.

In the LA-NBP class, the lowest  $K_i$  value at the  $\sigma_1$  receptor was displayed by ligand **(R)-5**; in the LA-DBMA series, the best  $\sigma_1$  receptor affinity values were displayed by enantiomeric mixtures of compounds **6** and **7**, which differ for the position of the amidic substituent on the central aromatic ring (3-position for compound **6** and 4-position for compound **7**) (Figure 5). Both compounds showed  $K_i$  values in the nanomolar range, with no enantioselectivity.

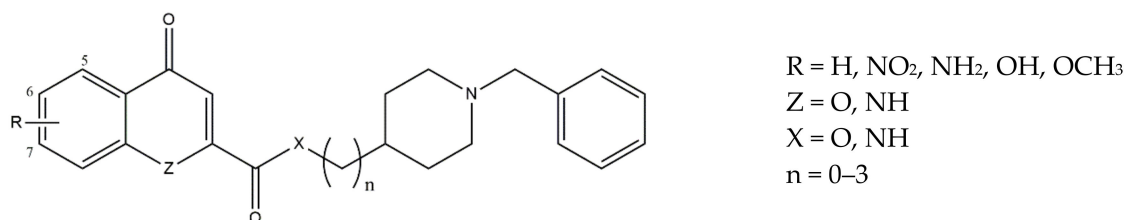


**Figure 5.** Compounds **(5,6)** and **(7)** structures and pharmacological profile for  $\sigma$  receptor ( $\sigma_1$  R and  $\sigma_2$  R), human acetylcholinesterase (*h*AChE), human butyrylcholinesterase (*h*BuChE),  $\beta$ -secretase 1 (BACE1), Oxygen Radical Absorbance Capacity (ORAC) and parallel artificial membrane assays (PAMPA-BBB) [99].

In addition, compounds **5** and **7** showed promising in vitro absorption, distribution, metabolism, excretion and toxicity (ADMET) properties, as they are able to cross the BBB by in vitro parallel artificial membrane assays (PAMPA-BBB). They also displayed low or moderate cytotoxicity in the SH-SY5Y neuroblastoma cell line (supporting their  $\sigma_1$  agonist or partial agonist rather than antagonist activity) [99].

In order to develop a more holistic strategy to hit AD, the same group designed novel MTDLs to target monoamine oxidase A (MAO-A), monoamine oxidase B (MAO-B), lipoxygenase-5 (5-LOX), AChE/BuChE, and  $\sigma_1$  receptors. Additionally, ROS attenuation and mechanisms of differentiation of neural stem cells were taken into account for these novel compounds. Thus, twenty-nine new Donepezil-flavonoid hybrids (DFHs) were synthesized. The *N*-benzylpiperidine fragment was connected through an amide or ester linker to the 4-oxo-4*H*-chromene flavonoid scaffold, which is endowed with MAO-A, MAO-B, and 5-LOX inhibitory activity, as well as antioxidant, anti-inflammatory, and neurogenic properties. Moreover, the flavonoid scaffold underwent some modifications such as substitution of the 4-oxo-4*H*-chromene with a quinoline-4(1*H*)-one or quinoline and the introduction of hydroxyl/methoxy groups on the aromatic ring.

Three classes of compounds (i.e., 4-chromenone, 4-quinolone, and quinoline-2-carboxamide) were tested for their activity at AChE/BuChE, 5-LOX, and MAOs as well as for their BBB permeability and antioxidant capacities. A restricted group of ligands belonging to the 4-chromenone and 4-quinolone classes (general structure in Figure 6) was selected and tested at  $\sigma$  receptors, showing low nanomolar  $K_i$  values ( $0.98 \text{ nM} > K_i > 47.4 \text{ nM}$ ) and selectivity versus the  $\sigma_2$  subtype. The best affinities were obtained when a single hydrogen-bond acceptor group ( $\text{NO}_2 > \text{NH}_2 > \text{OH} > \text{OCH}_3$ ) was in the 6-position of either the 4-oxo-chromene or 4-oxo-quinoline system, while the length of the linker between the amide and the *N*-benzylpiperidine groups had no influence on the affinity for  $\sigma_1$  receptors.



**Figure 6.** General structures of 4-chromenone and 4-quinolone classes of ligands.

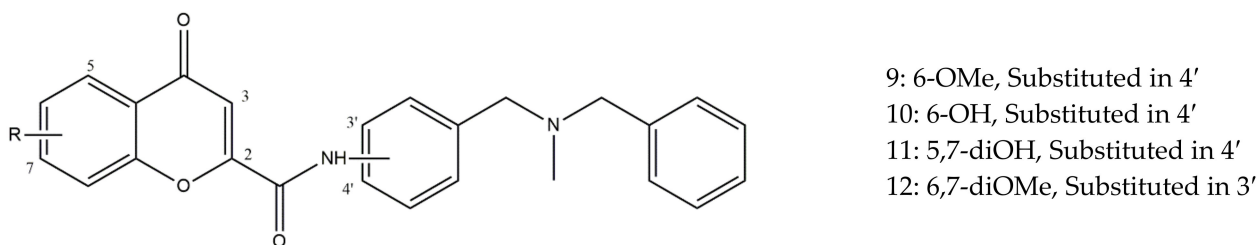
The best compromise among all studied compounds is represented by compound **8** (R = 6,7-diOMe; Z = O; X = NH and n = 2, Figure 6), which showed good neuroprotective properties: *h*AChE IC<sub>50</sub> = 46 nM; *h*BuChE IC<sub>50</sub> >10000 nM; PAMPA-BBB =  $5.9 \times 10^{-6} \text{ cm s}^{-1}$ ; 5-LOX IC<sub>50</sub> = 74.3  $\mu\text{M}$ ; MAO-A IC<sub>50</sub> = 15.3  $\mu\text{M}$ ; MAO-B IC<sub>50</sub> = 5.2  $\mu\text{M}$ ; ORAC = n.a.;  $\sigma_1$  R  $K_i$  = 37.4 nM;  $\sigma_2$  R  $K_i$  = 239 nM.

Moreover, compound **8** was shown to promote the differentiation of adult mice neural stem cells (NSC), and its predicted metabolites have been analyzed using the Derek Nexus program and shown to be not toxic. Additionally, docking by Molecular Dynamics (MD) simulation into AChE, 5-LOX, and the  $\sigma_1$  receptor showed low  $\Delta G_{\text{bind}}$  values in agreement with the experimentally detected interactions with the three targets. Based on these data, compound **8** was proposed as a promising candidate against AD and neurodegenerative diseases in general [100].

Based on these encouraging data, the same group developed other MTDLs targeting AChE/BuChE, BACE1, MAOs, 5-LOX, the differentiation of neural stem cells, and  $\sigma_1$  receptors. With this aim, the already exploited flavonoid cores (i.e., 4-chromenone or 4-quinolone) were conjugated with the *N,N*-dibenzyl-*N*-methylamine (DBMA) fragment, which was chosen for its proven interaction with the catalytic anionic site (CAS) of AChE. The two classes of 4-chromenone and 4-quinolone derivatives were tested, and the best compromise was obtained with ligands belonging to the former class. The most promising



ligands (i.e., **9**, **10**, **11**, and **12**, Figure 7) were also tested at  $\sigma_1$  and  $\sigma_2$  receptors, showing comparable sub-micromolar affinities for  $\sigma_1$  and micromolar affinities for  $\sigma_2$  receptors. These results showed that functionalization in 3' or 4' of the central benzene ring as well as changes in the position of the methoxy/hydroxy groups on the 4-chromenone scaffold poorly influence the  $\sigma$  receptors' affinity.



**Figure 7.** General structure of 4-chromenone-*N,N*-dibenzyl-*N*-methylamine (DBMA) derivatives.

Despite its low affinity and selectivity for  $\sigma_1$  receptors ( $\sigma_1$  R  $K_i = 0.53 \mu\text{M}$ ;  $\sigma_2$  R  $K_i = 1.30 \mu\text{M}$ ), compound **12** represented the best compromise in terms of activity toward different targets (*hAChE*  $\text{IC}_{50} = 4.5 \mu\text{M}$ ; *hMAO-A*  $\text{IC}_{50} > 100 \mu\text{M}$ ; *hMAO-B*  $\text{IC}_{50} > 100 \mu\text{M}$ ; 5-LOX  $\text{IC}_{50} = 30.4 \mu\text{M}$ ; and PAMPA-BBB =  $18.8 \times 10^{-6} \text{ cm s}^{-1}$ ).  $\Delta G_{\text{bind}}$  values obtained through docking to AChE, 5-LOX, BACE1, and  $\sigma_1$  were in agreement with the experimental ones, while a relatively safe profile was predicted in terms of toxicity. However, a low-confidence alert (below 67%) for human ether-a-go-go-related gene (*hERG*) channel inhibition was recorded, so that cardiac toxicity might be expected with this compound, which needs to be ascertained with further experimental studies. Neurogenic evaluation was performed on a primary culture of neural stem cells from the SGZ of adult rats, and compound **12** stimulated differentiation. Altogether, these data suggest compound **12** as a possible therapeutic agent that promotes brain auto-repair processes and blocks early steps of neurodegenerative cascades [101].

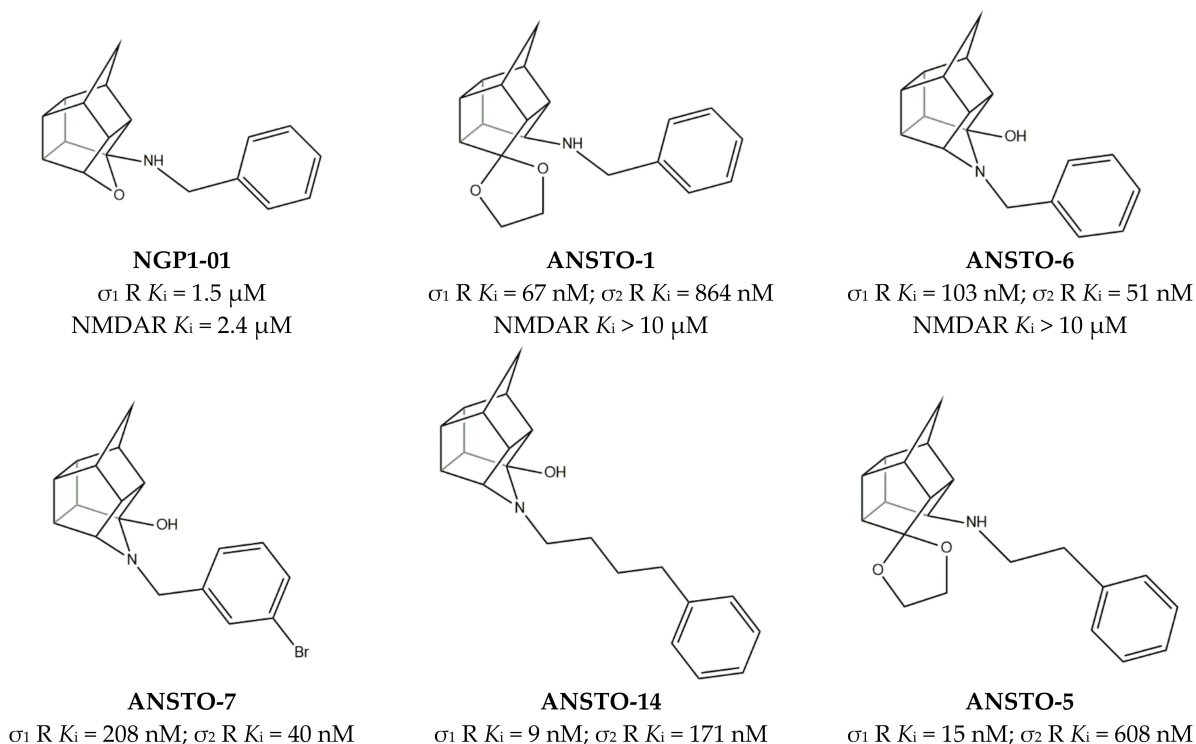
### 3.4. MTDLs Acting at $\sigma_1$ , NMDA Receptors, and VGCC

NMDA receptors are glutamate-gated  $\text{Ca}^{2+}$  permeable ion channels associated with  $\sigma_1$  receptors. In 1987, Quirion et al. identified the  $\sigma_1$  receptor as the phencyclidine (PCP) binding site [102], but further studies performed by the same group refuted the thesis and classified  $\sigma$  receptors as a separate class [103]. However, a strong connection between these two receptors has been found in the following years.  $\sigma_1$  Receptors can enhance  $\text{Ca}^{2+}$  influx via NMDAR, but they can also prevent toxicity induced by the excessive flux of this cation. This activity occurs through the modulation of NMDAR-associated intracellular signaling component, i.e., the neuronal Nitric Oxide Synthase (nNOS), which produces nitric oxide (NO) [104].

Low doses (100 nM) of  $\sigma_1$  receptor agonists enhance NMDAR function, producing a potentiation of the NMDAR response. Curiously, high doses ( $\geq 10 \mu\text{M}$ ) do not exert a stronger effect. Indeed, a bell-shaped dose–response trend, which is typical of the  $\sigma_1$  receptor agonists-mediated action, can be observed accounting for the majority of the effects of  $\sigma_1$  receptor agonists on NMDAR response [105,106]. A potential explanation of this effect is that  $\sigma_1$  receptor agonists can directly bind NMDARs and block channel conductance [107], but further studies are needed to solve the question. Moreover, the NMDAR increased activity is fast and prolonged [108], so that interactions also with other targets may be involved [104]. Even if these mechanisms have not been completely clarified, an interaction between the  $\sigma_1$  receptor and NMDAR exists. In particular, as recently reviewed,  $\sigma_1$  receptors can associate together with GluN1, Glun2a, and Glun2b subunits [17].

Taking into consideration all these aspects, dual drugs acting on  $\sigma_1$  and NMDA receptors may be a promising strategy to target neurodegenerative disorders.

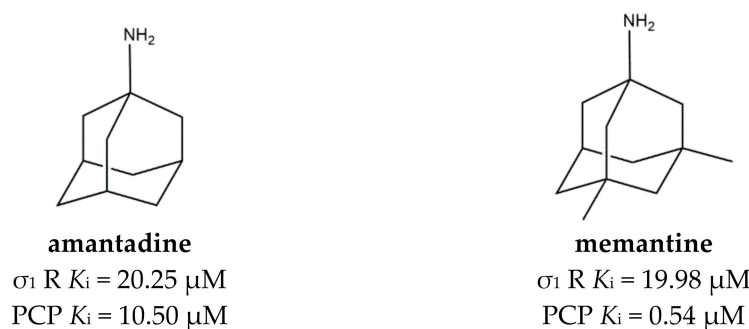
With the aim to discover potentialities of the aza-cage compound of the pentacyclo-[5.4.0.0<sup>2,6</sup>.0<sup>3,10</sup>.0<sup>5,9</sup>]undecane ring system (PCU), Van der Schyf et al. engaged physiological studies using sheep Purkinje fibers. These studies classified **NGP1-01** (Figure 8) as the lead compound of a novel class of Ca<sup>2+</sup> channel antagonist having a “cage” molecular structure [109].



**Figure 8.** NGP1-01, ANSTO-1, ANSTO-6, ANSTO-14, and ANSTO-5 structures and their  $K_i$  values for  $\sigma$  receptor ( $\sigma_1$  R and  $\sigma_2$  R) and N-methyl-D-aspartate receptor (NMDAR) [110–112].

Subsequent studies demonstrated the multi-target profile of **NGP1-01** evidenced by its ability to reduce Ca<sup>2+</sup> influx through interaction with L-type voltage-gated calcium channel (VGCC) [113] and NMDAR, with an activity comparable to the NMDAR antagonist **memantine** [114].

The discovery that **amantadine** had micromolar  $K_i$  values for  $\sigma$  receptors [115] led to investigate whether cage compounds could bind  $\sigma$  receptors. The micromolar affinity for  $\sigma_1$  receptors of **NGP1-01** inspired the synthesis of new trishomocubanes pentacyclo-[5.4.0.0<sup>2,6</sup>.0<sup>3,10</sup>.0<sup>5,9</sup>]undecylamines and 4-azahexacyclo[5.4.1.0<sup>2,6</sup>.0<sup>3,10</sup>.0<sup>5,9</sup>.0<sup>8,11</sup>]dodecanes, such as **ANSTO-1** and **ANSTO-6** (Figure 8). These compounds showed good affinity for  $\sigma$  receptors but low affinity for NMDAR (i.e., **ANSTO-1** and **ANSTO-6**, Figure 9) [110,111].



**Figure 9.** Amantadine and memantine structures and their  $K_i$  values for  $\sigma_1$  receptor ( $\sigma_1$  R) and the phencyclidine binding site at the N-methyl-D-aspartate receptor (PCP) [115].

The subsequent SAR, 3D-QSAR, and docking studies clarified the following: (i) azatrishomocubane derivatives have high affinity for both  $\sigma$  receptors; (ii) affinity for  $\sigma_1$  receptors is higher when the chain is longer; (iii) *para*- or *meta*-substitution with halogens is well tolerated, but the absence of substituents produces the highest selectivity and the lowest  $K_i$  value for  $\sigma_1$  receptors (**ANSTO-14**, **ANSTO-5**, and **ANSTO-7**, Figure 8) [103,104].

Nevertheless, the improved  $\sigma_1$  receptor affinity was accompanied by a dramatic loss in the affinity for NMDARs. Consequently, **NGP1-01** can still be considered the best MTDL in the class of the cage compounds.

Deeper studies able to clarify the mechanism of the  $\sigma_1$  receptors-mediated antineurodegenerative activity of **NGP1-01** are not available, to the best of our knowledge, but the affinity of the compound for the  $\sigma_1$  receptor and the antineurodegenerative properties mediated by the reduction of  $\text{Ca}^{2+}$  influx have been demonstrated, qualifying **NGP1-01** as a potential MTDL that is useful in the treatment of neurodegenerative pathologies.

Among cage compounds, **amantadine** and **memantine** (Figure 9) deserve to be mentioned because of their well-known antagonistic activity at the phencyclidine (PCP) binding site of NMDARs [116] together with the already mentioned affinity for  $\sigma_1$  receptors [115]. However, while the affinity of **memantine** at NMDARs is around 40-fold higher than the affinity at  $\sigma_1$ , **amantadine** interacts to the same extent with  $\sigma_1$  and NMDARs. Additionally, Peeters et al. confirmed the agonist  $\sigma_1$  receptor profile and shed the light on **amantadine** ability to positively increase dopaminergic transmission through the activation of  $\sigma_1$  receptors [117]. Therefore, **amantadine** can be considered a full-fledged MTDL.

### 3.5. MTDLs Acting at $\sigma_1$ Receptor/Dopaminergic Transmission

$\sigma_1$  Receptors are also associated with the dopaminergic transmission. BRET, coimmunoprecipitation (Co-IP), and proximity ligation assays studies demonstrated that  $\sigma_1$  receptors interact with dopamine (DA)  $D_1$  and  $D_2$  receptors, as well as with dopamine transporter (DAT) [17]. Beneficial effects of the  $\sigma_1$  chaperone function on dopaminergic transmission may be exploited in pathologies such as AD, PD, Huntington's disease (HD), and schizophrenia.

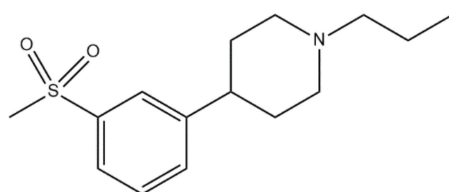
Interactions with  $D_1$  receptors were studied by Moreno et al. that performed in vitro and ex vivo assays, which led to identify, in the presence of **cocaine**, the formation of a heterotrimer composed of  $\sigma_1$ , histamine  $H_3$ , and  $D_1$  receptors. Upon the formation of this trimer, the inhibition of  $D_1$  receptors was abolished, and  $G_s$  proteins were activated with an increase of cAMP, recruitment of  $\beta$ -arrestin, and increase in p-ERK1/2 levels [118]. As a result,  $\sigma_1$  antagonists have the potential to reduce **cocaine** effects and consequent **cocaine** addiction.

$\sigma_1$  Receptors can also form heteromers with the  $D_2$  receptor. Biophysical, biochemical, and cell biology assays performed on mouse striatum demonstrated that the administration of cocaine can induce the formation of  $\sigma_1$ - $D_2$  dimers, inhibiting the downstream signaling [119].

Finally,  $\sigma_1$  receptors are also able to associate with DAT and reduce DAT-mediated dopamine efflux produced by **methamphetamine** exposure [120].

A large number of dopaminergic agents have been examined to better define their pharmacological profiles, and some of them were found to bind  $\sigma_1$  receptors, in accordance with a partially overlapping pharmacophore.

For a long time, **Pridopidine** (Figure 10) has been considered a dopaminergic antagonist because of its micromolar affinity for  $D_2$  receptors, but some in vivo data and its structural resemblance to the  $\sigma_1$  receptor ligands inspired Sahlholm and co-workers to perform studies that defined **Pridopidine** as a highly selective  $\sigma_1$  receptor agonist [63,121].

**Pridopidine**

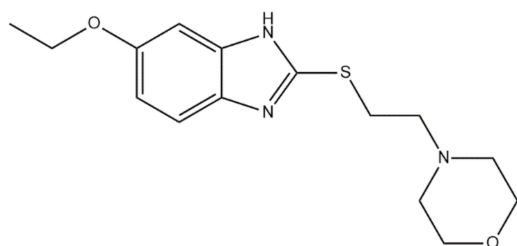
$\sigma_1$  R  $K_i$  = 0.057  $\mu$ M;  $\sigma_2$  R  $K_i$  = 5.45  $\mu$ M  
 $D_2$  R  $K_i$  = 29.5  $\mu$ M;  $\alpha_{2c}$  R  $K_i$  = 1.58  $\mu$ M; 5-HT<sub>1A</sub> R  $K_i$  = 3.63  $\mu$ M

**Figure 10.** Pridopidine structure and its  $K_i$  values for  $\sigma$  ( $\sigma_1$  R and  $\sigma_2$  R), dopaminergic  $D_2$  ( $D_2$  R), alpha-2c adrenergic ( $\alpha_{2c}$  R) and serotonergic 5-HT<sub>1A</sub> (5-HT<sub>1A</sub> R) receptors [75].

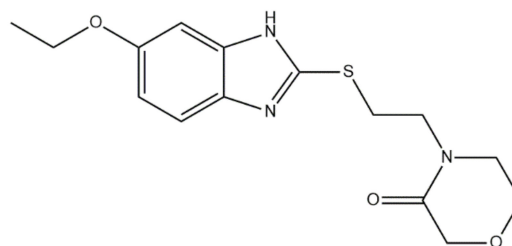
To better understand the neuroprotective and neurorestorative role of **Pridopidine**, Francardo et al. assayed the drug in a mouse model of Parkinson's disease (unilateral 6-hydroxydopamine (6-OHDA) lesion). After 5 weeks of daily administration of a low dose (0.3 mg/kg), **Pridopidine** produced an improvement in forelimb use and abolished the ipsilateral rotational bias typical of hemiparkinsonian animals. Moreover, the protection of nigral cell bodies, increased dopaminergic fiber density in the striatum, striatal upregulation of glial cell line-derived neurotrophic factor (GDNF), and brain-derived neurotrophic factor (BDNF) and phosphorylated extracellular signal-regulated kinases 1/2 (ERK1/2) were also observed [122]. At higher doses, **Pridopidine** was able to interact with other targets such as alpha-2 adrenergic  $\alpha_{2C}$  and serotonin 5-HT<sub>1A</sub> receptors, providing a solution to reduce L-dopa-induced dyskinesia (LID), both in PD and HD [75]. Of note, a phase III trial is in progress to evaluate the efficacy and safety of **Pridopidine** in HD patients (PRidopidine's Outcome on Function in Huntington Disease, PROOF-HD, ClinicalTrials.gov Identifier: NCT04556656). Importantly, promising data of **Pridopidine** for the treatment of AD are emerging as the compound prevents mushroom spine loss in hippocampal cultures from APP knock-in (APP-KI) and presenilin-1-M146 V knock-in (PS1-KI) mice [123].

The ability to functionally interact with different receptors identifies **Pridopidine** as a MTDL, which is useful in the treatment of neurodegenerative disease.

**Afobazole** (Figure 11) is an anxiolytic drug designed and pharmacologically studied by FSBI "Research Zakusov Institute of Pharmacology", Russia. This drug binds melatonin MT<sub>1</sub> ( $K_i$  = 16  $\mu$ M) and MT<sub>3</sub> ( $K_i$  = 0.97  $\mu$ M) receptors. MT<sub>3</sub> is a regulatory site of quinone reductase 2 enzymes (NQO2), which is responsible for ROS production. For this reason, the reversible inhibition performed by **Afobazole** produces a cytoprotective effect.

**Afobazole**

$\sigma_1$  R  $K_i$  = 5.9  $\mu$ M  
 $MT_1$  R  $K_i$  = 16  $\mu$ M;  $MT_3$  R  $K_i$  = 0.97  $\mu$ M  
 MAO-A  $IC_{50}$  = 3.6  $\mu$ M

**M-11**

$\sigma_1$  R  $K_i$  = 790  $\mu$ M  
 $MT_1$  R  $K_i$  = 44  $\mu$ M;  $MT_3$  R  $K_i$  = 0.39  $\mu$ M  
 MAO-A  $IC_{50}$  = 180  $\mu$ M

**Figure 11.** Afobazole and M-11 structures and their  $K_i$  and  $IC_{50}$  values for  $\sigma_1$  receptor ( $\sigma_1$  R), melatonin MT<sub>1</sub> and MT<sub>3</sub> receptors ( $MT_1$  R and  $MT_3$  R) and monoamine oxidase A (MAO-A), [124].

Some studies performed on **Afobazole** metabolites revealed that one of them, M-11, can bind the MT<sub>3</sub> receptor ( $K_i$  = 0.39  $\mu$ M) with a slightly higher affinity, while a lower

affinity is associated to the  $MT_1$  receptor ( $K_i = 44 \mu M$ ). Consequently, **Afobazole** activity can be considered empowered by the additive activity of its metabolite **M-11** (Figure 11) [124].

**Afobazole** can also inhibit MAO-A, thus increasing adrenaline, noradrenaline, and dopamine levels in CNS. Additionally, it also behaves as a  $\sigma_1$  receptor regulator, producing a cytoprotective effect through the inhibition of ROS production [125].

The need to clarify the involvement of  $\sigma_1$  receptors in neurodegenerative diseases inspired some studies on the 6-OHDA-induced parkinsonism model in mice. The study revealed that the administration of **Afobazole** (2.5 mg/kg, *i.p.*) over 14 days was able to restore motor dysfunction as well as prevent decreases in dopamine in the 6-OHDA-lesioned striatum and the loss of tyrosine hydroxylase positive (TH+) neurons in the substantia nigra. Importantly, these activities were abolished by the administration of the  $\sigma_1$  receptor antagonist **BD-1047** (3.0 mg/kg, *i.p.*), demonstrating that the effects of **Afobazole** are mediated by the  $\sigma_1$  receptor [126].

These pieces of evidence prove a strict connection between the dopaminergic transmission and the  $\sigma_1$  receptor and encourage more in-depth investigation to clarify the mechanisms involved.

With high affinity and antagonist properties at  $D_2$  receptors, **Haloperidol** (Figure 12) equally binds the  $\sigma_1$  receptor, behaving as an antagonist [127].

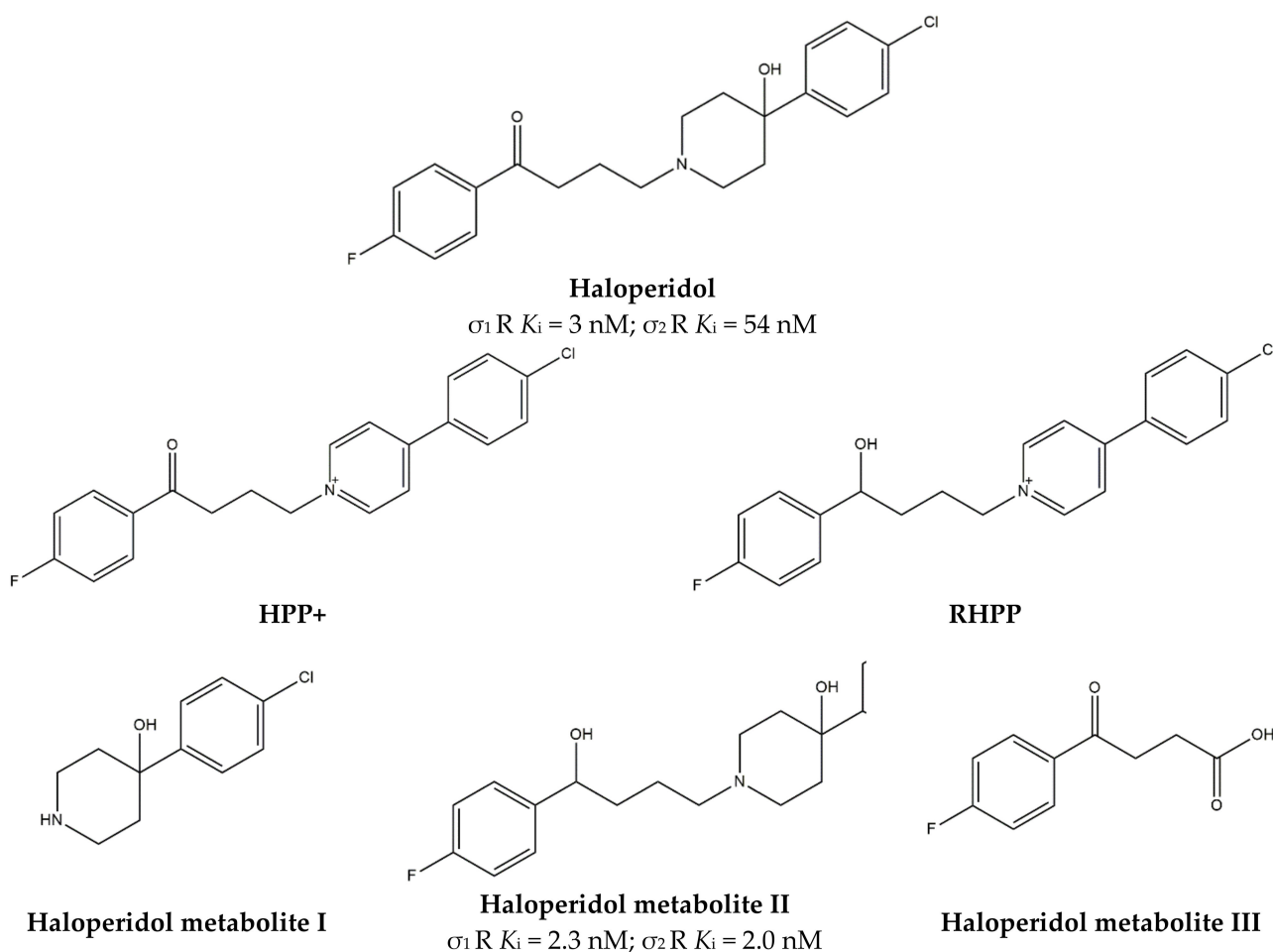


Figure 12. Haloperidol and its metabolites with  $K_i$  values for  $\sigma_1$  and  $\sigma_2$  receptors ( $\sigma_1 R$  and  $\sigma_2 R$ ) [127–129].

After administration, **Haloperidol** undergoes a complex metabolism that leads to toxic metabolites such as 4-(4-chlorophenyl)-1-[4-(4-fluorophenyl)-4-oxybutyl]pyridinium ion (HPP+) and 4-(4-(chlorophenyl)-1-4-(fluorophenyl)-4-hydroxybutyl-pyridinium (RHPP+) (Figure 12). In addition, also non-toxic metabolites have been observed (HP metabolites), such as HP metabolite II [130] and HP metabolites I and III [131] (Figure 12). Biological



activities of the non-toxic HP metabolites (I, II, and III) were studied, and in particular, their affinities for  $\sigma_1$  receptors were evaluated. While HP metabolite III does not bind  $\sigma_1$  receptors, HP metabolite I exerts a reversible inhibition, and HP metabolite II exerts an irreversible inhibition at the  $\sigma_1$  receptor. Thus, haloperidol metabolites can reinforce its action [128].

Further studies are needed to better understand the exploitability of this pharmacological activity, but preliminary data suggest that  $\sigma_1$  receptor antagonists, such as **Haloperidol**, could be useful in blocking the acute toxicity and the rewarding effects of cocaine because of an influence on the DA release (pre-synaptic activity) and reduction of  $\text{Ca}^{2+}$  mobilization produced by the activation of  $\text{D}_1$  receptors (post-synaptic activity) [132]. The additional activity of **Haloperidol** and its active metabolites could be foreseen in the antinociceptive action occurring through the modulation of opioid receptors [133].

Moreover, studies performed by Marrazzo and colleagues revealed that HP metabolite II is also able to exert anticancer activity because of its antagonism at the  $\sigma_1$  receptor and agonism at the  $\sigma_2$  receptor [134]. A more detailed discussion of HP metabolite II anticancer potentialities is reported in Section 3.7.

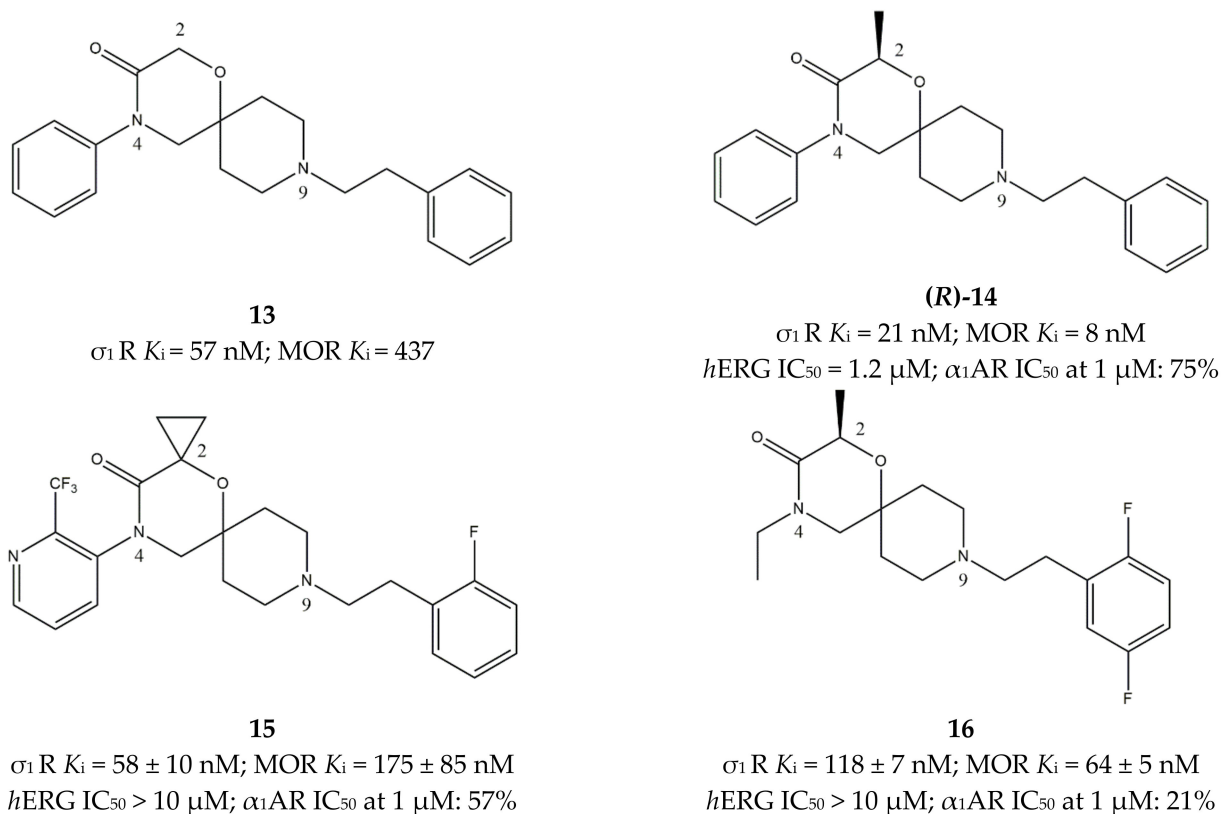
### 3.6. MTDLs Acting at $\sigma_1$ and $\mu$ -Opioid Receptors

One of the most difficult challenges in medicinal chemistry is represented by the synthesis of drugs able to manage pain for a prolonged period. In particular, chronic pain therapies are often associated with the adaptation phenomenon that is responsible for most of the side effects of these drugs, because it leads to periodic increases of the doses to be administered in order to keep the analgesia. Opioids, with their generally low therapeutic index, are still the most effective class of drugs able to relieve pain, making the need to increase the dose extremely life-threatening.

With this in mind, Garcia et al. developed a heterogeneous class of ligands with the aim to reinforce the antinociceptive activity mediated by  $\mu$ -opioid receptor (MOR) agonists with an antagonist activity at the  $\sigma_1$  receptor that has a well-established role in the treatment of pain. Some pieces of evidence have demonstrated that the antagonist **S1RA** [124,127] is able to potentiate morphine antinociceptive activity without increasing side effects, so that it entered clinical trials for treating different kinds of pain [135,136].

These premises paved the way to the development of a pharmacophore model obtained by overlapping the MOR pharmacophore generated with the “Auto Pharmacophore generation” protocol (that enumerates all the pharmacophores compatible with an input molecule considering hydrogen bond acceptors and donors, hydrophobic portions, ionizable groups, and aromatic rings) within the Discovery Studio [137] with the  $\sigma_1$  pharmacophoric model developed by Langer [138]. This model was based on the presence of two hydrogen bond acceptors (*HBA1* and *HBA2*), three hydrophobic portions (*HYD1*, *HYD2*, and *HYD34*, obtained by the fusion of two different hydrophobic portions *HBA3* and *HBA4* of Laggner’s pharmacophore), an aromatic ring (*AR*) and two positive ionizable domains (*PIs*).

Based on this model, several compounds were synthesized, and the 4-aryl-1-oxa-4,9-diazaspiro[5.5]undecane derivative **13** (Figure 13) provided the best results on both targets.



**Figure 13.** Compounds (13–16) and their  $K_i$  and  $IC_{50}$  values for  $\sigma_1$  ( $\sigma_1 R$ ),  $\mu$ -opioid (MOR) and alpha-1 adrenergic ( $\alpha_1AR$ ) receptors and human ether-a-go-go-related gene channel ( $hERG$ ) [139,140].

Starting from compound **13**, SAR studies were performed to optimize the structure. In particular, the 2-position on the spiro[5.5]undecane was explored through the introduction of small substituents such as methyl groups (compound **(R)-14**, Figure 13), which increased the activity mediated by MOR and  $\sigma_1$  receptors, while reducing the activity at the  $hERG$  channel, which was responsible for its cardiac toxicity. Moreover, pure enantiomers were tested demonstrating that **(R)-14** is 4-fold less active toward  $hERG$  and displays a 1-order of magnitude higher affinity for MOR than its (*S*)-counterpart. Elongation of the same alkyl group from methyl to ethyl or isopropyl produced an increase in the activity toward MOR but decreased the activity toward  $\sigma_1$  receptors, thus spoiling the beneficial synergy. Substitution with more polar groups produced compounds characterized by a lower affinity than compound **(R)-14**, but the activity at the two targets reached a more balanced compromise. Nevertheless, the reduction in lipophilicity did not improve the profile at  $hERG$ , which remained quite similar to the inhibition exerted by the more hydrophobic compound **(R)-14**.

Another structural exploration was conducted by introducing substituents on the phenyl ring on the 4-position of the 1-oxa-4,9-diazaspiro[5.5]undecane system. In particular, halogens and trifluoromethyl groups in *ortho* positions provided the best results toward the two targets, which was probably because of an increase in steric bulk. On the other hand, no improvement toward  $hERG$  inhibition was observed. Position 4 was also explored by introducing heteroaryl groups, and the best results were obtained when 2- or 3-pyridyl systems were inserted. As for the 9-position on the 1-oxa-4,9-diazaspiro[5.5]undecane system, the best results were obtained with the same groups introduced in position 4.

Among all of these compounds, **15** (Figure 13) resulted as the best compromise because of its activity toward the two targets and appreciable selectivity, with the most important achievement represented by the absence of  $hERG$  inhibition.

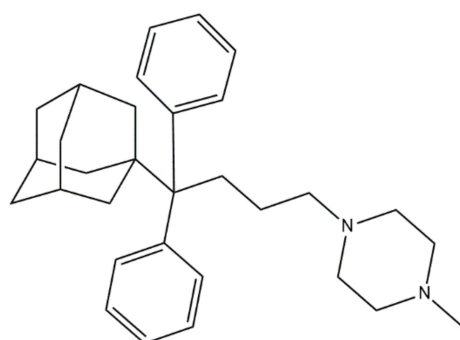
The promising pharmacodynamic profile, together with good solubility, moderate basicity and lipophilicity, and in vitro metabolic stability of compound **15** led the group to

study its antinociceptive properties in vivo. Results from the preclinical model, based on the mechanical pressure test on a hindpaw, demonstrated a dose-dependent antinociceptive effect with an ED<sub>50</sub> of 15 mg/kg after *i.p.* administration. Moreover, local administration of the compound provided promising results [139]. Further optimization of the compound was conducted with the production of new dual ligands with enhanced activity. Replacement of the aromatic ring in the 4-position of the 1-oxa-4,9-diazaspiro[5.5]undecane system with an ethyl group provided encouraging data. In fact, small alkyl groups produced a slightly reduced affinity toward MOR and  $\sigma_1$  receptors but considerably improved the profile toward alpha-1 adrenergic receptor ( $\alpha_1$ AR) and *h*ERG, which was likely because of a reduced lipophilicity. As already shown by structural changes leading to compound **14**, different small alkyl substituents were well tolerated at the 2-position (spirocyclopropyl, ethyl, and (*R*)-methyl groups), improving the affinity toward the two targets and the *h*ERG profile. These optimization studies led to compound **16** (Figure 13), which showed good physicochemical properties, high BBB permeability, and no cytotoxic activity in the hepatocarcinoma HepG2 cells. For these reasons, compound **16** was successfully tested in the paw pressure test and in the partial sciatic nerve ligation (PSNL) model in CD1 male mice. Thus, compound **16** was selected as a Phase 1 clinical candidate in the treatment of pain [140].

### 3.7. $\sigma_1$ Receptor and Cancer in a MTDLs Approach

The  $\sigma_1$  receptor is a well-established target in the neurodegenerative field. However, several cancer cell lines (e.g., *lung*: H69, H2019, H510; *breast*: MDA-MB-361, MDA-MB-435, BT20, MCF-7, T47D, MDA-MB-231, MDA-MB-468, SKBR3, BT474; *prostate*: PC3, LNCaP, LAPC4, C4-2, 22Rv1, VCaP, PC3, DU145; *human esophageal squamous cell carcinoma*: KYSE150, KYSE180, EC109; *pancreas*: Panc1; *liver*: HepG2; *neuroblastoma*: SK-N-BE(2)C) show high levels of  $\sigma_1$  proteins or SIGMAR1 transcripts. While the receptor is not an oncogene [141],  $\sigma_1$  receptor ligands with claimed antagonist activity exert antiproliferative and growth-inhibiting effects [142].

The involvement of the  $\sigma_1$  receptor in cancer prompted Riganas et al. to develop (1-adamantyl)diarylalkylamines as  $\sigma_1$  receptor ligands whose scaffold was based on two aromatic rings and a hydrophobic adamantane moiety, which were linked to an amine site through alkyl chains of different length. The activity of these ligands was also tested on Na<sup>+</sup> channels, whose involvement in cancer has been proven [141,143]. Compounds from the butyl series displayed the best profile with good  $\sigma_1$  receptor antagonist and weak  $\sigma_2$  receptor agonist activities, while all the other compounds showed a lower selectivity for  $\sigma_1$  vs.  $\sigma_2$ . Moreover, all of them showed from micromolar to sub-micromolar affinities for the site 2 of Na<sup>+</sup> channels. Compound **17** (Figure 14) emerged for its cytotoxic effect in ovarian cancer cells (IGROV-1) and in vitro antiangiogenic activity in normal cell lines such as Human Umbilical Vein Endothelial Cells (HUVEC).



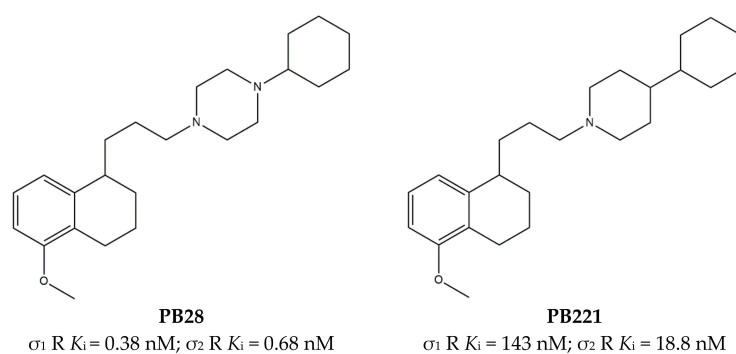
**17**

$\sigma_1$  R IC<sub>50</sub> = 15 nM;  $\sigma_2$  R IC<sub>50</sub> = 60 nM  
Na<sup>+</sup> channel IC<sub>50</sub> = 0.8  $\mu$ M

**Figure 14.** Compound (**17**) structure and its IC<sub>50</sub> values for  $\sigma_1$  receptor ( $\sigma_1$  R),  $\sigma_2$  receptor ( $\sigma_2$  R) and Na<sup>+</sup> channel [144].

Compound **17** was characterized by high-affinity interaction with the  $\sigma_2$  receptor as agonist (i.e., inducer of cytotoxicity) and with the  $\sigma_1$  receptor as antagonist, representing the optimal compromise if anticancer agents based on  $\sigma$  receptors-mediated action want to be produced. Additionally, **17** was associated with an analgesic effect against neuropathic pain, which was probably due to the block of  $\text{Na}^+$  channels, thus highlighting the therapeutic potentials of the combination of these actions in one molecule [145].

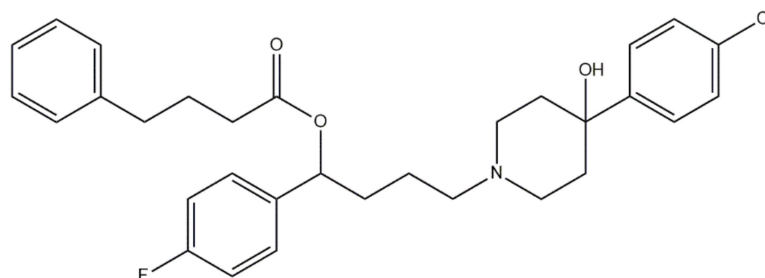
Another ligand conveniently endowed with antagonism at  $\sigma_1$  receptors and agonism at  $\sigma_2$  receptors is **PB28**, which has been found as a potential anti SARS-CoV-2 agent, and for this reason, researchers have recently reviewed its structure–affinity/activity relationships [144,146]. This compound emerged from structure–affinity relationship (SAfiR) studies that clearly indicated how *N*-alkyl-piperazine connected through a methylene linker to a hydrophobic nucleus (i.e., tetralin), rather than the corresponding *N*-Aryl ones, addressed the  $\sigma$  receptors affinity, and weakened the interaction with dopamine  $\text{D}_2$  and serotonin  $5\text{-HT}_{1A}$  receptors [71,147]. With its sub-nanomolar affinity toward both  $\sigma$  receptor subtypes, and the combination of functional activities ( $\sigma_1$  antagonism and  $\sigma_2$  agonism), **PB28** was tested in several cancer cells (e.g., breast, neuroblastoma, pancreas tumor cell lines) [144]. Moreover, studies performed in pancreatic cancer cell lines (i.e., Panc02, KP02, KCKO, MIA PaCa-2, BxPC-1, and Panc-1) highlighted the increase in ROS production, lysosomal membrane permeabilization (LMP), and mitochondrial superoxide production as **PB28** mechanisms of action that lead to oxidative stress [148]. However, the **PB28** anticancer effect both in vitro and in a preclinical model was not striking despite the promising  $\sigma$  binding profile. With the aim of increasing the cytotoxic activity, structural changes were made and several analogues of **PB28** were synthesized, some of which were endowed with promising anticancer action. As an example, the piperidinyl analogue **PB221** (Figure 15), with reduced  $\sigma$  receptor affinity and a more  $\sigma_2$ -oriented profile, was thoroughly investigated in CNS tumors and displayed promising results in preclinical models [149]. Additionally, the cytotoxic activity of **PB28** in resistant tumors was increased through the generation of multi-target ligands directed toward  $\sigma$  receptors (the  $\sigma_2$  receptor in particular) and P-glycoprotein, with the aim to evade the P-gp efflux whose overexpression is responsible for the drug-resistance phenomenon. While most of the compounds were active both in resistant and wild-type (wt) cancer cells [150], some MTDLs were endowed with the collateral sensitivity phenomenon that is characterized by more potent cytotoxicity in resistant rather than in the wt cells. The promising data obtained prompted to push the MTDL concept further in this context by merging the  $\sigma$ /P-gp scaffold with a metals chelator portion in order to stress the collateral sensitivity property thanks to the more important impact that the chelation of metals, such as iron and copper ions, has on the energy state of cells [151]. Excellent results were obtained with this class of compounds with a thiosemicarbazone structure that showed advantages in preclinical pancreatic tumor models, where the  $\sigma$ -mediated delivery to pancreatic tumors appeared devoid of side effects [152]. However, the  $\sigma_1$  involvement was not investigated in the overall effect, as focus on the  $\sigma_2$  subtype was given.



**Figure 15.** **PB28** and **PB221** structures and  $K_i$  values for  $\sigma_1$  receptor ( $\sigma_1$  R) and  $\sigma_2$  receptor ( $\sigma_2$  R) [153,154].

**PB28**, also **Haloperidol metabolite II** (Figure 12), is characterized by a  $\sigma_1$  receptor antagonism/ $\sigma_2$  receptor agonism profile, and it is able to exert modest antiproliferative activity because of the increase in the Intracellular-Free Calcium Levels  $[Ca^{2+}]_i$  and apoptosis induction [155].

This evidence supported the synthesis of **(R,S)-MRJF4** (Figure 16), which combined the **Haloperidol metabolite II** profile together with 4-phenylbutyric acid, which inhibits Histone Deacetylase (HDAC) and is involved in the transcription of genes that regulate the cell cycle, with a clear role in cancerogenesis and cancer progression.



**(R,S)-MRJF4**  $\sigma_1$  R  $K_i$  = 162 nM;  $\sigma_2$  R  $K_i$  = 105 nM

**(R)-MRJF4**  $\sigma_1$  R  $K_i$  = 87.5 nM;  $\sigma_2$  R  $K_i$  = 52.7 nM

**(S)-MRJF4**  $\sigma_1$  R  $K_i$  = 230 nM;  $\sigma_2$  R  $K_i$  = 118 nM

**Figure 16.** **(R,S)-MRJF4** structure and  $K_i$  values for  $\sigma_1$  receptor ( $\sigma_1$  R) and  $\sigma_2$  receptor ( $\sigma_2$  R) [129].

The esterification of **Haloperidol metabolite II** with 4-phenylbutyric acid appeared to be detrimental for the affinity toward both classes of receptors, with a drop from nanomolar to low micromolar values. Nevertheless, antiproliferative studies demonstrated that **(R,S)-MRJF4** is able to produce a more potent antiproliferative effect in LNCaP and PC3 than 4-phenylbutyric acid or **Haloperidol metabolite II** alone or in combination [134].

In the following years, the pure enantiomers **(R)-MRJF4** and **(S)-MRJF4** were studied, showing that **(R)**-enantiomer has a higher affinity for both  $\sigma$  receptors and higher anticancer activity (Figure 16) [129].

Noteworthy are some studies performed by Nieto et al. about cancer-associated pain in which paclitaxel was used to induce allodynia. This effect was observed in wild-type mice but not in the SIGMAR1 KO mice. Moreover,  $\sigma_1$  receptors antagonists, such as **BD1063** and **S1RA** (Table 1), reverted paclitaxel-induced neuropathic pain in wild-type mice [156,157].

Altogether, these studies show that the antiproliferative and growth-inhibiting activity of  $\sigma_1$  receptor antagonists can be empowered and likely better oriented when associated to other activities. Importantly, these same antagonists can block cancer-associated pain, which is an effect probably strengthened by the block of  $Na^+$  channels, thus again supporting the MTDLs approach involving  $\sigma_1$  receptors also in the treatment of pain associated to cancer.

#### 4. Conclusions and Perspectives

This review aims to point out the state of the art of MTDLs interacting with the  $\sigma_1$  receptor. As a result of its pluripotent chaperone activity, the  $\sigma_1$  receptor has the potential to interact and modulate several targets involved in a number of diseases and syndromes. The evidence that several compounds already in clinical use (e.g., **Donepezil**, **HP**, etc.) unintentionally bind the  $\sigma_1$  receptor has shed light on the already exploited interaction with this protein as a successful strategy in treating illnesses or associated symptoms through a MTDLs approach. **Donepezil**, whose interaction with  $\sigma_1$  receptors in vivo has been ascertained by receptor occupancy studies in the human brain [94,158], is co-administered together with Memantine through prescription medicines (i.e., **Namzaric**). On this basis, the rational development of MTDLs with a  $\sigma_1$  intentional targeting profile may lead to



more important therapeutic actions. The amount of herein listed proteins, which are the object of the MTLDs development in association with the  $\sigma_1$  receptor, is not intended to be exhaustive. Other proteins may be taken into consideration in the MTLDs development, considering the wide range of  $\sigma_1$  receptor direct and indirect interactors. Cannabinoid type-2 (CB2) receptors are an example, with recent support from computational methods that point out a partial overlap of the  $\sigma_1$  and CB2 receptors' pharmacophores [159]. These data strongly suggest the adoption of a merging approach for the development of dual  $\sigma_1$ /CB2 receptors ligands for a synergistic exploitation of the pathways activated by the two targets in oncology and neurodegenerative diseases. A number of  $\sigma$  ligands, besides interacting at the two subtypes (see Section 3.7), are able to modulate the efflux pump P-glycoprotein (P-gp) [150,160]. This double action is worthy of being more intentionally addressed, as it may serve as a strategy to face drug-resistant tumors: the compound overcomes P-gp, which is overexpressed in many resistant tumors and exerts its cytotoxic activity (as a  $\sigma_1$  antagonist). Importantly, this same double action may also have a role in the treatment of CNS diseases through the bypass of the P-gp at the BBB. The waving interest in  $\sigma$  receptors research increased during the COVID-19 pandemic, when the proteins were found as important key host dependency factors for coronavirus infections. However, while the exploitability of the  $\sigma_1$  receptor as a druggable target against coronavirus still needs to be fully investigated and validated, it appears clear that this protein is involved in a plethora of pathways hampered in multifactorial CNS and cancer diseases, rendering the  $\sigma_1$  receptor a full-fledged target for the development of multifunctional therapeutics.

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