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## **Discovery and mapping of an intracellular antagonist binding site at the chemokine receptor CCR2**

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**Running title: Intracellular binding site at the chemokine receptor CCR2**

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**Abbreviations:**

BCA, bicinehoninic acid;

BSA, bovine serum albumin;

CHAPS, 3-((3-cholamidopropyl)-dimethylammonio)-1-propanesulfonate;

CHO, Chinese hamster ovary;

CCR2, C-C chemokine receptor 2;

CXCR4, C-X-C chemokine receptor 4;

DMEM, Dulbecco's modified eagle medium;

DPBS, Dulbecco's phosphate buffered saline;

EC<sub>50</sub>, half maximal effective concentration;

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ECL, extracellular loop;

EDTA, ethylenediaminetetraacetic acid;

GPCR, G protein-coupled receptor;

HA, hemagglutinin;

HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid;

HRP, horseradish peroxidase;

IC<sub>50</sub>, half maximal inhibitory concentration;

ICL, intracellular loop;

IP, inositol phosphate;

IT1t, isothiourea derivative;

NEAA, non-essential amino acids;

PBS, phosphate buffered saline;

PEI, polyethyleneimine;

TBS, Tris-buffered saline;

TM, trans-membrane;

U2OS-CCR2: human osteosarcoma cells stably expressing CCR2;

WT, wild-type;

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## Abstract

The chemokine receptor CCR2 is a G protein-coupled receptor that is involved in many diseases characterized by chronic inflammation, and therefore a large variety of CCR2 small molecule antagonists has been developed. On the basis of their chemical structures these antagonists can be roughly divided into two groups with most likely two topographically distinct binding sites. The aim of the current study was to identify the binding site of one such group of ligands, exemplified by three allosteric antagonists, CCR2-RA-[R], JNJ-27141491 and SD-24. We first used a chimeric CCR2/CCR5 receptor approach to obtain insight into the binding site of the allosteric antagonists, and additionally introduced eight single point mutations in CCR2 to further characterize the putative binding pocket. All constructs were studied in radioligand binding and/or functional IP turnover assays, providing evidence for an intracellular binding site for CCR2-RA-[R], JNJ-27141491 and SD-24. For CCR2-RA-[R] the most important residues for binding were found to be the highly conserved tyrosine Y<sup>7.53</sup> and phenylalanine F<sup>8.50</sup> of the NPxxYX<sub>(5,6)</sub>F motif, as well as V<sup>6.36</sup> at the bottom of TM-VI and K<sup>8.49</sup> in helix-VIII. These findings demonstrate for the first time the presence of an allosteric intracellular binding site for CCR2 antagonists. This contributes to an increased understanding of the interactions of diverse ligands at CCR2 and may allow for a more rational design of future allosteric antagonists.

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## Introduction

The chemokine receptor CCR2 is a G protein-coupled receptor (GPCR) that is expressed on monocytes, dendritic cells, activated T lymphocytes and basophils, and therefore it plays an important role in the immune system (Fantuzzi et al., 1999; Jimenez et al.; Luster, 1998). These immune cells migrate towards increasing concentrations of chemokines at sites of inflammation as part of the immune response, also known as chemotaxis. CCR2 is activated by multiple chemokines, including CCL2, CCL7, CCL8, CCL11, CCL13 and CCL16. Besides its important role in physiology, increased levels of CCR2 and its ligands can induce severe tissue damage. This results in a large variety of diseases that are characterized by chronic inflammation (Boring et al., 1998; Mahad and Ransohoff, 2003; Quinones et al., 2005; White et al., 2005), which makes CCR2 an attractive drug target for the pharmaceutical industry. As a consequence many CCR2 small molecule antagonists have been developed over the years, but unfortunately all clinical candidates tested so far appeared to lack efficacy in man.

Most small molecule chemokine receptor antagonists bind at the main binding pocket in the upper half (exterior part) of the transmembrane (TM) helices, usually with one part in the so-called major binding pocket (surrounded by TM helices III, IV, V, VI and VII) and the other part in the minor binding pocket (surrounded by TM helices I, II, III and VII) (Surgand et al., 2006). Many small molecule antagonists contain a positively charged basic nitrogen that interacts with the conserved negatively charged glutamic acid residue (E291<sup>7,39</sup>) in TM-VII, which is directly located in between the major and minor binding pocket (Rosenkilde and Schwartz, 2006). An example of such a CCR2 antagonist is INCB3344 (Fig. 1), to which we refer as an orthosteric antagonist, since it was previously reported to inhibit CCR2 in a competitive manner with respect to the chemokine ligand CCL2 (Shin et al., 2009; Zweemer et al., 2013). Interestingly, other classes of antagonists were discovered to bind at a different

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binding site than INCB3344 (Zweemer et al., 2013). It was shown that these antagonists, CCR2-RA-[R] and JNJ-27141491 (Fig. 1), possess structural features different from the orthosteric antagonists and inhibit CCR2 in a noncompetitive manner with respect to CCL2. The current study took these findings as the starting point to resolve the location of the binding site for these allosteric CCR2 antagonists. For several other chemokine receptors the presence of an allosteric binding site has been reported (Maeda et al., 2006; Scholten et al., 2011). Some of these antagonists bind exclusively to the major or minor binding pocket (Rosenkilde et al., 2010) and their binding site can even be directed towards the extracellular loops, as illustrated in the CXCR4 crystal structure for the small molecule antagonist IT1t (Wu et al., 2010). In addition, an allosteric binding site on the intracellular side of the receptor in the C-terminal domain has been suggested for the chemokine receptors CXCR2, CCR4 and CCR5 (Andrews et al., 2008; de Kruijf et al., 2009; Nicholls et al., 2008; Salchow et al., 2010).

In the present study we first showed that a previously described antagonist with a sulfonamide scaffold (SD-24) is also an allosteric antagonist (Fig. 1) (Peace et al., 2010). Subsequently, we used a CCR2/CCR5 chimeric approach to get insight into the binding site of allosteric antagonists for CCR2 and made single point mutations in CCR2 to further map this binding pocket. We discovered the existence of an intracellular binding site in CCR2 that is recognized by (at least) three chemically different classes of antagonists. Finally, we discuss the compounds' mechanism of action and the implications for targeting CCR2 in disease states.

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## Materials and Methods

**Chemicals and reagents.** CCL2 was purchased from PeproTech (Rocky Hill, NJ). INCB3344, JNJ-27141491 and CCR2-RA-[R] were synthesized according to published methods (Brodmerkel et al., 2005; Doyon et al., 2008; Xue et al., 2004; Zou et al., 2007). SD-24 (sulfonamide derivative #24 from the Peace et al. paper) was synthesized in-house, according to procedures described previously (Peace et al., 2010). [<sup>3</sup>H]-INCB3344 (specific activity 32 Ci mmol<sup>-1</sup>) and [<sup>3</sup>H]-CCR2-RA (specific activity 63 Ci mmol<sup>-1</sup>) were custom-labeled by Vitrax (Placentia, CA). <sup>125</sup>I-CCL2 (2200 Ci/mmol), <sup>125</sup>I-CCL3 (2200 Ci/mmol), [<sup>35</sup>S]GTP $\gamma$ S (1250 Ci/mmol) and *myo*-[<sup>3</sup>H]inositol (PT6-271) (94.5 Ci/mmol) were purchased from Perkin-Elmer (Waltham, MA, USA). Bovine serum albumin (BSA, fraction V) was purchased from Sigma (St. Louis, MO, USA). Bicinchoninic acid (BCA) and BCA protein assay reagent were obtained from Pierce Chemical Company (Rockford, IL, USA). Polyethyleneimine (PEI) was obtained from Polysciences Inc. (Warrington, PA, USA). Wild-type (WT) FLAG-tagged CCR5 was cloned in-house from a leukocyte cDNA library, while WT FLAG-tagged CCR2 cDNA was kindly provided by Dr Tim Wells (GlaxoSmithKline, UK). The chimeric receptor CCR5-CCR2<sub>all</sub>, was previously described (Thiele et al., 2011), whereas CCR2-CCR5<sub>C-term</sub> and CCR5-CCR2<sub>C-term</sub> were designed in-house and cloned using PCR overlap extension technique (Piscataway, NJ). pcDNA3.1+ plasmid containing the WT CCR2 with a 3x hemagglutinin (HA) epitope tag at the N-terminus was kindly provided by James Pease (Imperial College London, UK) (Hall et al., 2009). The promiscuous G protein G $\alpha_{\Delta 6qi4myr}$  (G<sub>qi4myr</sub>) was kindly provided by Evi Kostenis (University of Bonn, Germany). Tango CCR2-bla U2OS cells stably expressing human CCR2 (U2OS-CCR2) were obtained from Invitrogen (Carlsbad, CA). CHO (Chinese hamster ovary) cells were obtained from Hans den Dulk (Leiden University, the Netherlands) and COS-7 cells were obtained from

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ATCC (Rockville, MD). The monoclonal rabbit anti-HA-tag antibody and the HRP-conjugated goat anti-rabbit antibody were obtained from Novus Biologicals (Cambridge UK). The monoclonal mouse anti-FLAG M1 antibody was obtained from Sigma (St. Louis, MO) and the HRP-conjugated goat anti-mouse antibody was obtained from Pierce (Rockford, IL). AG 1-X8 anion exchange resin was obtained from Bio-Rad (Hercules, CA). All other chemicals were obtained from standard commercial sources.

**Site-directed mutagenesis.** pcDNA3.1+ plasmids containing the human CCR2 mutants I208A<sup>5.45</sup> and E291A<sup>7.39</sup> (superscript indicates the Ballesteros Weinstein numbering system (Ballesteros, 1995), in which transmembrane residues are assigned two numbers that belong to the helix number and the residue number relative to the most conserved residue in this helix, which is assigned 50) with a 3x hemagglutinin (HA) epitope tag at the N-terminus were kindly provided by James Pease (Hall et al., 2009). All other point mutations were generated by site-directed mutagenesis, using WT HA-tagged CCR2 plasmid DNA as a template for the generation of mutant plasmids by polymerase chain reaction (PCR) using the QuickChange® II Site-directed mutagenesis kit (Stratagene, the Netherlands) and the appropriate oligonucleotide primers (Eurogentec, the Netherlands), under conditions recommended by the manufacturer. All mutants were verified by DNA sequencing before use (LGTC, Leiden University, the Netherlands).

**Cell culture.** COS-7 cells and U2OS-CCR2 cells were cultured as described before (Thiele et al., 2011; Zweemer et al., 2013). Chinese hamster ovary (CHO) cells were cultured in Ham's F12 culture medium supplemented with 10% (v/v) newborn calf serum, penicillin (50 IU/mL) and streptomycin (50 µg/mL) at 37°C and 5% CO<sub>2</sub>. Cells were subcultured twice weekly at a ratio of 1:20 by trypsinization on 10-cm ø plates.



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**Transfections.** Transfections of COS-7 cells with FLAG-tagged CCR2, CCR5 or chimeric receptor were performed by the calcium phosphate precipitation method as described before (Kissow et al., 2012). Transfections of CHO cells with FLAG-tagged CCR2, CCR5 or chimeric receptor, as well as HA-tagged WT or mutant CCR2, were performed with polyethyleneimine (PEI). For this purpose, CHO cells were grown to 50-60% confluence on 15-cm  $\emptyset$  plates and transfected with 10  $\mu$ g of plasmid DNA per 15-cm  $\emptyset$  plate. Briefly, 10  $\mu$ g of plasmid DNA was diluted in a sterile 150 mM NaCl solution and subsequently mixed with PEI solution (1mg/mL) to obtain a DNA:PEI mass ratio of 1:6. The mixture was incubated for 20 min at room temperature before transfection. The culture medium of the cells was refreshed and 1 mL of DNA/PEI mixture was added to cells and incubated for 48 hrs at 37°C and 5% CO<sub>2</sub>.

**Cell membrane preparation.** Membranes were prepared as described before (Zweemer et al., 2013). Briefly, cells were scraped from 15-cm  $\emptyset$  plates upon which the membranes and cytosolic fractions were separated during several centrifugation steps. Finally, the membrane pellet was resuspended in ice-cold 50 mM Tris-HCl buffer containing 5 mM MgCl<sub>2</sub>, pH 7.4, and aliquots were stored at -80 °C. Membrane protein concentrations were measured using a BCA protein determination with BSA as a standard (Smith et al., 1985).

**Cell surface expression by Enzyme-Linked Immunosorbent Assay (ELISA).** For transfections with WT and mutant CCR2 receptors containing a HA-tag, CHO cells were plated 24 hrs after transfection at a density of  $1 \times 10^6$  cells per well in a 96-well plate and incubated at 37 °C and 5% CO<sub>2</sub> for 24 hrs. Cells were washed with PBS and incubated with rabbit anti-HA primary antibody (dilution 1:5000 in DMEM) for 30 min at RT. After a

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subsequent wash with DMEM/HEPES (25 mM), cells were incubated with HRP-conjugated goat anti-rabbit secondary antibody (dilution 1:5000 in DMEM) for 30 min at RT. The cells were washed twice with pre-warmed PBS, after which tetramethyl benzene (TMB) was added for 5 min in the dark at RT. The reaction was stopped by addition of 1 M H<sub>3</sub>PO<sub>4</sub> and after 5 min absorbance was measured at 450 nm with a Victor<sup>2</sup>V plate reader (Perkin Elmer, Waltham, MA, USA).

**<sup>125</sup>I-CCL2 binding assays.** <sup>125</sup>I-CCL2 and <sup>125</sup>I-CCL3 whole cell binding assays on COS-7 cells transfected with WT FLAG-tagged CCR2, CCR5 or chimeric receptor were performed as described before (Thiele et al., 2011). In these assays <sup>125</sup>I-CCL2 was used for CCR2 and the two chimeras CCR5-CCR2(all) and CCR2-CCR5(C-term), whereas <sup>125</sup>I-CCL3 was used for CCR5 and the chimera CCR5-CCR2(C-term). Briefly, the assay was performed at 4°C in a 200 µL reaction volume containing 50 mM Hepes buffer (pH 7.4), 5 mM MgCl<sub>2</sub>, 1 mM CaCl<sub>2</sub>, 0.5% bovine serum albumin and COS-7 cells transfected with receptor cDNA. The number of cells seeded per well was determined by the apparent expression efficiency of the receptors and was aimed at obtaining 5–10% specific binding of the added radioactive ligand. Non-specific binding was determined with 100 nM unlabeled CCL2 or CCL3 and reactions were terminated as described before. <sup>125</sup>I-CCL2 binding assays on U2OS-CCR2 cell membranes were performed as described before (Zweemer et al., 2013). Briefly, the assay was performed in a 100 µL reaction volume containing 50 mM Tris-HCl buffer (pH 7.4), 5 mM MgCl<sub>2</sub>, 0.1% 3-((3-cholamidopropyl)-dimethylammonio)-1-propanesulfonate (CHAPS) and 15 µg of U2OS-CCR2 cell membrane protein at 37°C. Displacement assays were performed with 0.1 nM <sup>125</sup>I-CCL2 using six concentrations of competing ligand for 150 min of incubation. At this concentration, total radioligand binding did not exceed 10% of the

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amount added to prevent ligand depletion. Non-specific binding was determined with 10  $\mu$ M INCB3344. Reactions were terminated as described before.

**[<sup>3</sup>H]-INCB3344 binding assays.** [<sup>3</sup>H]-INCB3344 membrane binding assays were performed as described before (Zweemer et al., 2013). For the FLAG-tagged CCR2, CCR5 and the chimera's expressed in CHO cells, homologous displacement studies were carried out with 2.1 nM and 5.0 nM [<sup>3</sup>H]-INCB3344 to be able to determine the equilibrium dissociation constant  $K_D$ . Full curve displacement studies with HA-tagged WT and mutant receptors of CCR2 were carried out with a single concentration of 5.7 nM [<sup>3</sup>H]-INCB3344. In all cases, eight concentrations of competing ligand were incubated for 120 min at 25°C. Non-specific binding for mutant and WT CCR2 receptors was determined in the presence of 10  $\mu$ M INCB3344. For the WT receptor the measured non-specific binding was equal to the experiments in which 10  $\mu$ M BMS22 was used, as described in our previous study (Zweemer et al., 2013). In all experiments, total radioligand binding did not exceed 10% of the amount added to prevent ligand depletion.

**[<sup>3</sup>H]-CCR2-RA binding assays.** [<sup>3</sup>H]-CCR2-RA membrane binding assay conditions were similar as those for [<sup>3</sup>H]-INCB3344 binding assays as described before (Zweemer et al., 2013). For the FLAG-tagged CCR2, CCR5 and the chimera's expressed in CHO cells, homologous displacement studies were carried out with 4.5 nM and 7.9 nM [<sup>3</sup>H]-CCR2-RA to be able to determine the equilibrium dissociation constant  $K_D$ . Displacement assays with HA-tagged WT and mutant receptors of CCR2 were carried out with a single concentration of 7.9 nM [<sup>3</sup>H]-CCR2-RA. In all cases, eight concentrations of competing ligand were incubated for 120 min at 25°C. Non-specific binding was determined in the presence of 10  $\mu$ M CCR2-RA-[R]. For the WT receptor the measured non-specific binding was equal to the experiments in which 10  $\mu$ M JNJ-27141491 was used, as described in our previous study (Zweemer et al.,

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2013). In all experiments, total radioligand binding did not exceed 10% of the amount added to prevent ligand depletion.

**Inositol Phosphate turnover (IP Turnover) assay.** IP turnover was measured in COS-7 cells co-transfected with WT FLAG-tagged CCR2, CCR5 or chimeric receptor and the promiscuous G protein G<sub>qi4myr</sub>, as described before (Thiele et al., 2011).

**[<sup>35</sup>S]GTPγS binding assay.** The [<sup>35</sup>S]GTPγS assay was performed as described before (Zweemer et al., 2013). To determine G protein activation of the wild-type and mutant CCR2 receptors, 10 μg of CHO cell membranes were pre-incubated with 100 nM CCL2 (single point) or six increasing concentrations of CCL2 for 30 min at 25 °C. Then [<sup>35</sup>S]GTPγS (0.3 nM) was added, after which the mixture was incubated for 90 min and samples were harvested as described before.

**Data analysis.** All experiments were analyzed using the non-linear regression curve fitting program Prism 5 (GraphPad, San Diego, CA, U.S.A.). pK<sub>D</sub> values for the FLAG-tagged CCR2, CCR5 and chimeric receptors were calculated using the homologous competitive binding curve fit. The pIC<sub>50</sub> values for WT and mutant CCR2 of INCB3344, CCR2-RA-[R], JNJ-27141491 and SD-24 were obtained by non-linear regression analysis of the displacement curves. Statistical analysis was performed with a two-tailed unpaired Student's *t*-test. All values obtained are means of at least three independent experiments performed in duplicate, unless stated otherwise.

**Homology modeling and ligand docking.** A homology model of the chemokine CCR2 receptor was constructed using the homology modeling tool within Maestro (Jacobson et al.,

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2002; Jacobson et al., 2004; Schrodinger, 2013a) (Data Supplement). This model was based on the structure of the chemokine CCR5 receptor co-crystalized with maraviroc (Protein Data Bank ID: 4MBS). The best model was selected based on the energy-based scoring function, while the sequence alignment between CCR2 and CCR5 was performed using ClustalW as implemented within Maestro. CCR2-RA-[R] was docked into the receptor homology model using the induced fit docking protocol (Schrodinger, 2013b; Sherman et al., 2006). The grid center was placed based on residues D78<sup>2.40</sup>, Y305<sup>7.53</sup>, K311<sup>8.49</sup> and F312<sup>8.50</sup> with an automatic box size. Visualizations were created using PyMOL version 1.5.0.4. (Schrodinger).

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## Results

**Effect of sulfonamide SD-24 on CCR2 radioligand binding.** The sulfonamide derivative SD-24 partially inhibited binding of  $^{125}\text{I}$ -CCL2 to CCR2-expressing U2OS cell membranes to  $27 \pm 6\%$  at  $10\ \mu\text{M}$ , with a  $\text{pIC}_{50}$  of  $7.2 \pm 0.2$  (Fig. 2).  $[\text{}^3\text{H}]$ -CCR2-RA was fully displaced with a  $\text{pK}_i$  value of  $9.0 \pm 0.1$ . On the contrary, SD-24 slightly increased  $[\text{}^3\text{H}]$ -INCB3344 binding to a maximum of 120% at  $1\ \mu\text{M}$  SD-24, indicating it binds at a site different from the previously described (Shin et al., 2009; Zweemer et al., 2013) orthosteric binding pocket of INCB3344 (Fig. 2).

**Comparison of CCR2 and CCR5.** In order to identify regions that are responsible for binding of SD-24 and the other allosteric antagonists we compared the affinity of CCR2-RA-[R], JNJ-27141491 and SD-24 for CCR2 and its close homolog CCR5 (Fig. 3A) in whole cell radioligand binding assays using  $^{125}\text{I}$ -CCL2 and  $^{125}\text{I}$ -CCL3, respectively. CCR2-RA-[R] and JNJ-27141491 displaced  $^{125}\text{I}$ -CCL2 from CCR2 with  $\text{pIC}_{50}$  values of  $6.1 \pm 0.1$  and  $6.6 \pm 0.1$ , respectively (Table 1, Fig. 4). In addition, JNJ-27141491 inhibited  $^{125}\text{I}$ -CCL3 from binding to CCR5 with a  $\text{pIC}_{50}$  value of  $5.4 \pm 0.1$ , whereas CCR2-RA-[R] did not sufficiently displace  $^{125}\text{I}$ -CCL3 from CCR5 to be able to determine its affinity for CCR5. The affinity of SD-24 for CCR2 could not be measured in this whole cell binding assay, and neither was any displacement of  $^{125}\text{I}$ -CCL3 from CCR5 observed in the presence of SD-24 (Table 1, Fig. 4). Differently, in the functional IP turnover assay the  $\text{pIC}_{50}$  values for CCR2 and CCR5 inhibition could be determined for all antagonists (Table 2, Fig. 4). In this assay CCR2-RA-[R], JNJ-27141491 and SD-24 showed a 7-fold, 14-fold and 22-fold increased potency to inhibit CCR2 compared to CCR5, respectively.

The orthosteric antagonist INCB3344 displaced the radioligands  $^{125}\text{I}$ -CCL2 and  $^{125}\text{I}$ -CCL3 from CCR2 and CCR5, respectively, with a  $\text{pIC}_{50}$  of  $7.8 \pm 0.2$  and  $5.3 \pm 0.2$  (Table 1,

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Fig. 4). Its  $pIC_{50}$  to inhibit IP turnover was  $8.0 \pm 0.01$  for CCR2 and  $5.3 \pm 0.01$  for CCR5 (Table 2, Fig. 4). In comparison to the allosteric antagonists, INCB3344 showed a much higher affinity (280-fold) and potency (460-fold) for CCR2 compared to CCR5.

To better determine the affinity of INCB3344 and CCR2-RA-[R] for CCR2 and CCR5 we performed homologous displacement assays, in which the antagonist radioligands were displaced by their chemically identical unlabeled ligands, on membrane preparations of CHO cells transfected with CCR2 and CCR5. The  $pK_D$  of INCB3344 for CCR2 was  $8.1 \pm 0.1$ , whereas binding to CCR5 could not be detected at nanomolar concentrations of [ $^3H$ ]-INCB3344. The  $pK_D$  of CCR2-RA-[R] for CCR2 and CCR5 was  $8.8 \pm 0.1$  and  $7.0 \pm 0.1$ , respectively (Table 3). All these data together suggest that the orthosteric small molecule binding site is more divergent between CCR2 and CCR5 than the allosteric small molecule binding pocket.

**CCR2-CCR5 chimeric approach.** Given the high structural similarity between CCR2 and CCR5, we took CCR5 as a template structure to further elucidate the allosteric binding site in CCR2. Therefore we decided to use a chimeric approach to investigate the role of the extracellular loops and intracellular region of the receptor in binding of the antagonists (Fig. 3B). The chimera CCR5-CCR2(all), which consisted of CCR2's extracellular receptor regions, and CCR5 for the remainder of the construct, was used to study the role of the extracellular loops for small molecule binding. In order to study the role of the C-terminus in binding of the antagonists, two novel chimera's were constructed; CCR5-CCR2(C-term) and CCR2-CCR5(C-term), consisting of CCR5 with CCR2 C-terminus, and CCR2 with CCR5 C-terminus, respectively. We confined ourselves to the C-terminus, as the intracellular loops are highly similar in sequence between CCR2 and CCR5 (Fig 3A).

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For the two allosteric antagonists CCR2-RA-[R] and JNJ-27141491, the ability to inhibit binding of  $^{125}\text{I}$ -CCL2 to CCR2 as well as the potency to inhibit IP<sub>3</sub> formation by CCL2 was not affected when the C-terminal part of CCR5 was introduced in CCR2 (CCR2-CCR5(C-term)) (Tables 1 and 2, Fig. 4). In addition, for CCR2-RA-[R] and JNJ-27141491 no difference was observed in their potency to inhibit IP<sub>3</sub> formation by CCL3 between CCR5 and CCR5-CCR2(C-term) (Table 2, Fig. 4). The displacement of  $^{125}\text{I}$ -CCL3 from CCR5-CCR2(C-term) by CCR2-RA-[R], JNJ-27141491 and SD-24 could not be compared to CCR5, since their affinities were too low in a number of cases (Table 1, Fig. 4). Similarly, SD-24 did not displace  $^{125}\text{I}$ -CCL2 binding from CCR2 and CCR2-CCR5(C-term) (Table 1, Fig. 4). However, the pIC<sub>50</sub> value of SD-24 to inhibit IP<sub>3</sub> formation via CCR5-CCR2(C-term) was with  $5.6 \pm 0.1$  slightly higher than the pIC<sub>50</sub> of  $5.3 \pm 0.1$  for CCR5. All together, the data of the IP turnover assay suggest that non-conserved residues in the C-terminus of CCR2 compared to CCR5 are not involved in binding of the allosteric antagonists CCR2-RA-[R] and JNJ-27141491. For SD-24, a 2-fold increase in potency was observed upon introduction of the CCR2 C-terminus in CCR5, whereas introduction of the CCR5 C-terminus in CCR2 did not result in any changes.

Upon introduction of the extracellular loops of CCR2 in CCR5 (chimer CCR5-CCR2(all)), a significant decrease in potency to inhibit IP turnover was observed for CCR2-RA-[R] as its pIC<sub>50</sub> value was  $5.2 \pm 0.2$  for CCR5-CCR2(all) compared to  $6.2 \pm 0.1$  in case of CCR5 (Table 2, Fig. 4). In the binding assays the affinities of CCR2-RA-[R] and SD-24 for CCR5-CCR2(all) were negligible (Table 1, Fig. 4). Differently, a slight decrease in affinity of JNJ-27141491 was observed, since its pIC<sub>50</sub> value was  $5.0 \pm 0.1$  for CCR5-CCR2(all) compared to  $5.4 \pm 0.1$  for CCR5 (Table 1, Fig. 4). It should be noted that we compared binding and activation of CCR5 by  $^{125}\text{I}$ -CCL3/CCL3 with binding and activation of CCR5-



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CCR2(all) by  $^{125}\text{I}$ -CCL2/CCL2. It can thus not be excluded that activation of these receptors in a molecularly different way could be responsible for the observations.

In contrast to the allosteric antagonists, the inhibitory potency and affinity of the orthosteric antagonist INCB3344 was increased for CCR5 when the extracellular loops of CCR2 were introduced. INCB3344 inhibited  $^{125}\text{I}$ -CCL3 binding to CCR5 and  $^{125}\text{I}$ -CCL2 binding to CCR5-CCR2(all) with a  $\text{pIC}_{50}$  of  $5.3 \pm 0.2$  and  $6.3 \pm 0.1$ , respectively (Table 1, Fig. 4). In addition, the potency of INCB3344 to inhibit CCL2-induced CCR5-CCR2(all) activity in the functional assay was increased 45-fold compared to its potency to inhibit CCL3-induced CCR5 activity (Table 2, Fig. 4). Next we measured the effect of the C-terminus swap on the affinity and potency of INCB3344. For CCR2-CCR5(C-term) the affinity of INCB3344 and its potency to inhibit IP turnover were not significantly altered compared to CCR2. Exchange of the CCR5 C-terminus with that of CCR2 made INCB3344 unable to displace  $^{125}\text{I}$ -CCL3 from CCR5-CCR2(C-term), whereas the potency to inhibit IP turnover was similar for CCR5-CCR2(C-term) compared to CCR5.

The small molecule radioligands [ $^3\text{H}$ ]-INCB3344 and [ $^3\text{H}$ ]-CCR2-RA were only able to bind to CCR2-CCR5(C-term) of all three chimers, with a  $\text{pK}_D$  of  $8.6 \pm 0.1$  and  $8.7 \pm 0.1$ , respectively (Table 3). Thus no significant change compared to the WT CCR2  $\text{pK}_D$  of  $8.8 \pm 0.1$  was observed for [ $^3\text{H}$ ]-CCR2-RA, in agreement with the chemokine-displacement assays (Table 1 and 3). [ $^3\text{H}$ ]-INCB3344 was found to bind slightly better to CCR2-CCR5(C-term) compared to CCR2 ( $\text{pK}_D = 8.1 \pm 0.1$ ), somewhat different than observed in the chemokine-displacement assays (Table 1 and 3).

**Identification of intracellular residues involved in CCR2-RA-[R] binding.** To further investigate the possibility of an intracellular binding pocket, we applied a site-directed mutagenesis approach. We initially constructed four mutations in CCR2, K72A<sup>2,34</sup>, D78N<sup>2,40</sup>,

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Y305A<sup>7.53</sup> and K311A<sup>8.49</sup> (Fig 3A+C). K72<sup>2.34</sup> in ICL1 is one of the few differential residues in the intracellular loops of CCR2 compared to CCR5 (Fig. 3A). Y305<sup>7.53</sup> is very conserved among G protein-coupled receptors, whereas D78<sup>2.40</sup> and K311<sup>8.49</sup> are typical residues among chemokine receptors (see also Discussion). As a control we included I208A<sup>5.45</sup>, which was previously not predicted in any binding site, and E291A<sup>7.39</sup>, which is the highly conserved acidic residue in the orthosteric binding pocket of chemokine receptors. All six mutant receptors were expressed at the cell surface, as determined by whole cell ELISA (Fig. 5).

Mutation of Y305<sup>7.53</sup> into an alanine residue (Y305A) completely abolished [<sup>3</sup>H]-CCR2-RA binding, whereas the affinity of [<sup>3</sup>H]-INCB3344 was not affected (Table 4). The affinity of CCR2-RA-[R] for the K311A<sup>8.49</sup> mutant receptor was 10-fold decreased compared to WT CCR2, whereas the K72A<sup>2.34</sup> and D78N<sup>2.40</sup> mutations did not affect binding. The affinity of INCB3344 was not affected by any of these mutations at the intracellular region (Table 4). In contrast, the affinity of INCB3344 was 8-fold decreased for the E291A<sup>7.39</sup> mutant receptor compared to WT CCR2, whereas the affinity of CCR2-RA-[R] was not affected by this mutation located in the upper half of the receptor. These results reveal that the two residues Y305<sup>7.53</sup> and K311<sup>8.49</sup>, both located at the transmembrane/intracellular side of the receptor, are involved in binding of the allosteric antagonist CCR2-RA-[R], whereas E291<sup>7.39</sup> in the orthosteric binding pocket is only important for binding of INCB3344 to CCR2.

**Docking of CCR2-RA-[R] in a CCR2 homology model.** To obtain further insight in the binding pose of CCR2-RA-[R], we constructed a CCR2 homology model (Data Supplement) using the crystal structure of CCR5 (PDB: 4MBS) and docked the antagonist CCR2-RA-[R] in the model. When standard docking was used, only low scoring poses were found. Therefore we employed induced-fit docking to account for the flexibility of the intracellular pocket. Final poses were selected based on both the score and consistency with

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experimental results. In Figure 5 the interactions of CCR2-RA-[R] with V244<sup>6.36</sup>, K311<sup>8.49</sup>, Y305<sup>7.53</sup> and F312<sup>8.50</sup> are visualized. The pocket is shielded by Y305<sup>7.53</sup> at the top and F312<sup>8.50</sup> at the side, both enabling hydrophobic interactions with CCR2-RA-[R]. K311<sup>8.49</sup> is turned towards the bottom of the binding pocket and interacts with one of the carbonyl oxygens in CCR2-RA-[R]. At the side of the binding pocket, V244<sup>6.36</sup> was found to interact with the hexyl-ring of CCR2-RA-[R]. The residues K72A<sup>2.34</sup> and D78<sup>2.40</sup> were not in close proximity to CCR2-RA-[R] (Fig. 6A), which was in agreement with their lack of effect on binding observed in the radioligand binding experiments (Table 4).

**Experimental evidence for the docking pose of CCR2-RA-[R].** We determined the effect of mutagenesis of V244<sup>6.36</sup> in TM-VI and F312<sup>8.50</sup> in helix-VIII on binding of [<sup>3</sup>H]-CCR2-RA, since these residues were predicted to be important for binding of CCR2-RA-[R] in the homology model. Both mutant receptors V244A<sup>6.36</sup> and F312A<sup>8.50</sup> were expressed at the cell surface, as determined by whole cell ELISA (Fig. 5). Similar to Y305A<sup>7.53</sup>, the binding of [<sup>3</sup>H]-CCR2-RA was completely abolished for V244A<sup>6.36</sup> and F312A<sup>8.50</sup>, while [<sup>3</sup>H]-INCB3344 was able to bind with a slightly increased affinity to both mutant receptors in comparison to WT CCR2 (Table 4).

**Effect of CCR2 mutations on receptor activation.** The effects of the mutations on receptor activation were determined in a [<sup>35</sup>S]GTP $\gamma$ S assay. [<sup>35</sup>S]GTP $\gamma$ S binding was equal for mock transfected CHO cell membranes as for WT CCR2 CHO cell membranes (data not shown), and therefore no basal activity is reported in Figure 7. The mutations K72A<sup>2.34</sup>, V244<sup>6.36</sup>, E291A<sup>7.39</sup>, Y305A<sup>7.53</sup>, K311A<sup>8.49</sup> and F312A<sup>8.50</sup> distorted receptor activation as no [<sup>35</sup>S]GTP $\gamma$ S binding window was observed upon addition of 100 nM CCL2 (Fig 7A). CCL2 was found to induce G protein-activation for WT CCR2 with a pEC<sub>50</sub> value of 7.6  $\pm$  0.2 (Fig.

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7B). D78N<sup>2.40</sup> was the only mutant receptor that allowed significant G protein-activation by CCL2, which yielded a pEC<sub>50</sub> value of 7.8 ± 0.1 (Fig. 7B).

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## Discussion

Since the early days of GPCR research, our understanding of ligands that activate or inhibit these receptors has increased dramatically (De Lean et al., 1980; Furchgott, 1964). We can now distinguish GPCR ligands with a broad spectrum of activities and mechanisms of action, which implies the presence of multiple binding sites, including so-called allosteric binding sites (Wootten et al., 2013). In the present study we provided evidence for the presence of an allosteric intracellular binding site for small molecule antagonists of the chemokine receptor CCR2.

Without knowing their location on the receptor we have previously reported on multiple binding sites for small molecule CCR2 ligands, and classified CCR2-RA-[R] and JNJ-27141491 as allosteric antagonists based on radioligand binding studies (Zweemer et al., 2013). Besides these, we now identified the antagonist SD-24 to bind at the same allosteric binding pocket at CCR2 (Fig. 2). SD-24 partially displaced the orthosteric agonist  $^{125}\text{I}$ -CCL2, whereas it enhanced binding of the orthosteric antagonist [ $^3\text{H}$ ]-INCB3344. This behavior is indicative for allosteric modulation and probe dependency, as the effect observed with the allosteric modulator SD-24 depends on the nature of the receptor probe used to make the measurement (Kenakin, 2005; Lazareno and Birdsall, 1995). Ligands structurally related to SD-24 with a pyrazinyl-sulfonamide scaffold have been reported to bind at the intracellular side of CCR4 (Andrews et al., 2008). Although the precise location of this binding site was not identified, interactions of these antagonists with the C-terminus of CCR4 were reported.

In order to elucidate the location of the CCR2 binding site for CCR2-RA-[R], JNJ-27141491 and SD-24, we constructed several CCR2-CCR5 chimeric receptors to identify regions responsible for binding. CCR2 and CCR5 bear a high sequence similarity of approximately 70%, which makes them perfect candidates for the construction of chimeric receptors (Shields, 2000; Toda et al., 2009). Besides a suggested intracellular binding site on

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CCR4, CCR5, CXCR1 and CXCR2 (Andrews et al., 2008; Nicholls et al., 2008; Salchow et al., 2010), other allosteric ligands for chemokine receptors have been reported to interact with the extracellular loops (ECLs). ECL2 contributes to the CXCR4 binding site of the co-crystallized ligand It1 (Wu et al., 2010), and interactions with ECL2 were reported for the CCR5 antagonists AK530 (Maeda et al., 2008), aplaviroc (Thiele et al., 2011) and small molecule ligands targeting CCR1 and CCR8 (Jensen et al., 2012).

We constructed CCR2-CCR5 chimeras in which either these extracellular regions or the C-terminus were swapped. Binding of the orthosteric CCR2 antagonist INCB3344 was not affected after exchange of the C-terminus in the chemokine-displacement assays, but the binding to CCR5 was increased when extracellular loops of CCR2 were introduced. This fits very well with an orthosteric binding mode, since other small molecule chemokine receptor ligands that bind to the major binding pocket have been found to also interact with ECL2 (Jensen et al., 2012; Maeda et al., 2008; Thiele et al., 2011). However, CCR5 binding of the allosteric antagonists CCR2-RA-[R], JNJ-27141491 and SD-24 was not improved after introduction of the ECLs of CCR2. The affinity and potency of CCR2-RA-[R] and JNJ-27141491 did not change after swapping the C-terminus between CCR2 and CCR5, while for SD-24 a small but significant increase in potency was measured upon introduction of the CCR2 C-terminus in CCR5.

A remarkable discrepancy in antagonist affinity was observed between the whole cell binding assays and the membrane binding assays. The binding  $IC_{50}$  values of the allosteric ligands to CCR2 in the whole cell assays at 4 °C were much higher than the corresponding values in the membrane assays at 37 °C (Zweemer et al., 2013). Notably, SD-24 completely lacked inhibition of  $^{125}I$ -CCL2 binding in the whole cell assay, whereas a  $pIC_{50}$  of  $7.2 \pm 0.2$  was measured in the membrane binding assay (Table 1 and Fig. 2). It should be noted that intracellular antagonists need to pass the cell membrane before they can exert receptor

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inhibition in case of these whole cell assays. Although different cellular systems were used in these distinct assays, the antagonist binding to the intracellular binding pocket could also explain the decreased affinities in whole cell assays due to putative difficulties to enter the cell. Moreover, the whole cell binding assays were performed at 4°C, which might decrease passage through the membrane even further. The latter may also account for the large discrepancy in affinity and potency of the allosteric antagonists when comparing the data from the whole cell binding assays and whole cell functional assays. In these studies, the allosteric antagonists displayed up to 10-fold higher potency in the whole cell IP3 assay performed at 37 °C compared to their IC<sub>50</sub> in the whole cell binding assay performed at 4 °C, whereas INCB3344 behaved similarly in both assays. These results imply that membrane based binding assays may allow a more straightforward data interpretation for allosteric ligands that bind to the intracellular side of a GPCR.

To explore the possibility of an intracellular binding site, we focused on three conserved residues among chemokine receptors that were previously reported to be involved in small molecule binding at CXCR2, being D78<sup>2,40</sup>, Y305<sup>7,53</sup> and K311<sup>8,49</sup> (Salchow et al., 2010). The binding of [<sup>3</sup>H]-CCR2-RA was completely abolished for Y305A<sup>7,53</sup>, and a 10-fold decreased affinity was observed for K311A<sup>8,49</sup>. Upon considering the important GPCR motifs in this intracellular region and subsequent induced fit docking in a CCR2 homology model we identified F312<sup>8,50</sup> and V244<sup>6,36</sup> as part of the intracellular pocket, and mutagenesis of these residues into alanine completely prevented [<sup>3</sup>H]-CCR2-RA from binding. This data is in line with the unaffected affinity of the allosteric antagonists for the chimera's in which the C-terminus was swapped, since K<sup>8,49</sup> and F<sup>8,50</sup> are present in both CCR2 and CCR5.

Y305<sup>7,53</sup> is the highly conserved tyrosine in the NPxxY motif found in 92% of class A GPCRs and this motif has been shown to be important for receptor internalization, receptor signaling and activation (Fritze et al., 2003; Kalatskaya et al., 2004; Nygaard et al., 2009). For

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CCR2 we confirmed its critical role in signaling, since a loss of G protein-activation was observed for Y305A<sup>7.53</sup> (Fig. 8A). The increasing number of GPCR crystal structures show that Y305<sup>7.53</sup> can interchange between multiple different states (Hulme, 2013), which emphasizes the flexibility of this residue and therefore also its potential to contribute to the creation of an intracellular small molecule binding pocket.

Together with F312<sup>8.50</sup> which is conserved in 68% of class A GPCRs, Y305<sup>7.53</sup> forms the NPxxYx<sub>5,6</sub>F motif (Fritze et al., 2003). The  $\pi$ -stacking interaction between F312<sup>8.50</sup> and Y305<sup>7.53</sup> directly links TM-VII and helix-VIII and keeps the receptor in an inactive state (Nygaard et al., 2009), as observed in multiple crystal structures including the recent CCR5 structure (Tan et al., 2013). Upon activation, the aromatic stacking interaction is disrupted which allows Y305<sup>7.53</sup> to rotate into the helical TM core to permit receptor signaling (Hulme, 2013). In induced-fit docking with CCR2-RA-[R] we observed that Y305<sup>7.53</sup> likely shields the top of the binding pocket, whereas F312<sup>8.50</sup> is positioned between TM-VII and TM-I and may therefore contribute to hydrophobic interactions with the space-filling chlorine substituent on the phenyl ring of CCR2-RA-[R] (Fig. 6).

Besides Y305<sup>7.53</sup> and F312<sup>8.50</sup>, the residues V244<sup>6.36</sup> and K311<sup>8.49</sup> were found important for binding of CCR2-RA-[R]. K311<sup>8.49</sup> is a basic, positively charged residue and therefore a likely partner to interact with the partially negative charge on the oxygen present in CCR2-RA-[R] (Fig. 1 and 5). This interaction was visualized in the docking pose, in which K311<sup>8.49</sup> was found to shield the bottom of the binding pocket. K<sup>8.49</sup> is highly conserved among chemokine receptors (68.4%), but otherwise not prevalent among class A GPCRs (5.7%). Besides in CCR2, this residue was also found to be important in CXCR2 for interaction with the acidic Pteridone-1, Sch527123 and SB265610 antagonists (Nicholls et al., 2008; Salchow et al., 2010). It would be interesting to study whether such a basic residue at this position is



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facilitating the presence of a small molecule binding pocket, in view of the prevalence of intracellular antagonists among the chemokine receptor family so far.

The loss of [<sup>3</sup>H]-CCR2-RA binding upon the mutation of V244<sup>6,36</sup> into alanine confirms that TM-VI is involved in the creation of the intracellular small molecule binding pocket. Notably, it is TM-VI that moves outward on activation of GPCRs as has become evident from a comparison between active and inactive state crystal structures (Kruse et al., 2013). Besides steric hindrance by the antagonist for G protein binding, the fixation of TM-VI in an inactive state might be another mechanism by which these antagonists exert their inhibitory effect. Interestingly this valine residue is among the few differential intracellular residues between CCR2 and CCR5, since a leucine is present on this position in CCR5 (Fig. 3A). Clearly the presence of a valine is very important for high affinity binding of CCR2-RA-[R], and the extended alkyl chain of the leucine in CCR5 may cause steric hindrance preventing high affinity binding of CCR2-RA-[R].

Importantly, the affinity of the orthosteric antagonist INCB3344 was not affected for any of the mutations at the intracellular interface. Instead a significantly reduced affinity of INCB3344 was observed for the E291A<sup>7,39</sup> mutation (8-fold), as was published before for other orthosteric antagonists (Hall et al., 2009; Mirzadegan et al., 2000). Of note, this is the first study with experimental data that confirms the interaction of INCB3344 with E291<sup>7,39</sup> of CCR2 – a residue that is known to function as an anchor point for many positively charged CC-chemokine receptor small molecules (Mirzadegan et al., 2000; Rosenkilde and Schwartz, 2006). Interestingly a slight increase in INCB3344 affinity was observed for the F312A<sup>8,50</sup> and V244A<sup>6,36</sup> mutant receptors. This could imply that these mutants induce an inactive conformation of the receptor, in agreement with their lack of G protein-activation in the [<sup>35</sup>S]GTPγS assay, and thereby enhance binding of INCB3344.

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Intracellular binding sites have become subject of study over the past few years. The cytoplasmic tails of CCR4, CCR5 and CXCR1 have been implicated in the binding of antagonists, as were several specific intracellular residues for antagonists of CXCR2, including equivalent residues we studied (Andrews et al., 2008; Nicholls et al., 2008; Salchow et al., 2010). In addition, an allosteric modulator of the PAR1 receptor was found to act through helix-VIII (Dowal et al., 2011). In the current study we largely identified the location of this intracellular binding pocket for CCR2. Notably, we were for the first time able to visualize such an intracellular binding pocket upon induced-fit docking of CCR2-RA-[R] in a CCR2 homology model that was constructed based on the recent crystal structure of CCR5 (Tan et al., 2013). Previous attempts to predict the location of intracellular binding pockets in homology models most likely failed due to the lack of a closely related crystal structure (Salchow et al., 2010). This work provides a starting point for future studies on binding poses of related allosteric antagonists, such as JNJ-27141491 and SD-24.

In summary, the evidence for intracellular binding pockets at (chemokine) GPCRs is accumulating. The results of our mutagenesis and docking studies provide evidence for such an allosteric binding site on CCR2 at a defined location and may facilitate the design of novel intracellular antagonists for this and other chemokine receptors, and, hopefully, for GPCRs in general.

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## **Authorship contributions**

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*Conducted experiments:* Zweemer, Bunnik, Veenhuizen, De Vries, Miraglia, Thiele, Lenselink.

*Contributed new reagents or analytic tools:* Vilums, Gibert.

*Performed data analysis:* Zweemer, Bunnik, Veenhuizen, De Vries, Miraglia, Thiele.

*Wrote or contributed to the writing of the manuscript:* Zweemer, Lenselink, Thiele, Rosenkilde, IJzerman, Heitman.

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## **Footnotes**

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## Figure legends

**Figure 1.** Chemical structures of the orthosteric CCR2 antagonist INCB3344 and the allosteric CCR2 antagonists CCR2-RA-[R], JNJ-27141491 and SD-24.

**Figure 2.** Modulation of  $^{125}\text{I}$ -CCL2,  $[^3\text{H}]$ -INCB3344 and  $[^3\text{H}]$ -CCR2-RA binding to U2OS cell membranes stably expressing CCR2 by increasing concentrations of the CCR2 antagonist SD-24. Results are presented as percentage of bound radioligand for one representative experiment performed in duplicate. SD-24 inhibited binding of  $^{125}\text{I}$ -CCL2 with a  $\text{pIC}_{50}$  of  $7.2 \pm 0.2$  and  $[^3\text{H}]$ -CCR2-RA with a  $\text{pK}_i$  of  $9.0 \pm 0.1$ . For  $^{125}\text{I}$ -CCL2,  $27 \pm 6\%$  radioligand remained bound in the presence of  $10\ \mu\text{M}$  SD-24.

**Figure 3.** (A) Sequence alignment with ClustalW2 of CCR2 and CCR5, for which the transmembrane regions as well as the intracellular and extracellular loops are indicated (bottom). Differing residues are indicated with an asterisk, and CCR2 residues mutated in this study are indicated in black. The arrow presents the location where the C-termini were swapped. The locations where the extracellular loops of CCR2 were inserted into CCR5 can be found in Thiele *et al.* 2011. (B) Schematic representation of CCR5 and the chimeric receptors CCR5-CCR2(all), CCR2-CCR5(C-term) and CCR5-CCR2(C-term). (C) Schematic representation of CCR2. The approximate location of the residues  $\text{K}^{2.34}$ ,  $\text{D}^{2.40}$ ,  $\text{I}^{5.45}$ ,  $\text{V}^{6.36}$ ,  $\text{E}^{7.39}$ ,  $\text{Y}^{7.53}$ ,  $\text{K}^{8.49}$  and  $\text{F}^{8.50}$  is indicated.

**Figure 4.** Inhibition of chemokine whole cell binding and IP turnover activation by the small molecule antagonists, for CCR2, CCR5 and the chimeric receptors expressed in COS-7 cells. Graphical representation of the data in Tables 1 and 2, presented as mean  $\text{pIC}_{50} \pm \text{S.E.M.}$  of at

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least three experiments performed in duplicate. \*  $p < 0.05$  vs. CCR5, \*\*  $p < 0.005$  vs. CCR5, Student's t-test.

**Figure 5.** Surface expression of the HA-tagged WT and mutant CCR2 receptors in CHO cells as measured by ELISA. Data was normalized for WT CCR2 expression (100%) and is presented as mean  $\pm$  SD of at least two experiments performed in quadruplicate.

**Figure 6.** (A) Induced fit docking of CCR2-RA-[R] in a homology model of CCR2 based on the crystal structure of CCR5. The pocket is shielded by Y305<sup>7.53</sup> at the top and F312<sup>8.50</sup> at the side, K311<sup>8.49</sup> is turned towards the bottom of the binding pocket and V244<sup>6.36</sup> interacts at the side with the hexyl-ring. D78<sup>2.40</sup> and K72<sup>2.34</sup> are represented in yellow, as these residues are not predicted to interact with CCR2-RA-[R]. (B) Interaction map of CCR2-RA-[R] with surrounding residues upon induced fit docking.

**Figure 7.** (A) G protein-activation by CCL2 measured in a [<sup>35</sup>S]GTP $\gamma$ S binding assay on CHO cell membranes expressing WT and mutant CCR2 receptors. (B) Concentration-effect curves of CCL2 on WT and D78N<sup>2.40</sup> CCR2 resulting in a pEC<sub>50</sub> of  $7.6 \pm 0.2$  and  $7.8 \pm 0.1$ , respectively. A representative graph of one experiment performed in duplicate is shown.

**Data Supplement.** Homology model of CCR2 based on the structure of the chemokine CCR5 receptor co-crystalized with maraviroc (PDB ID: 4MBS).

## Tables

**Table 1.** Inhibition of chemokine whole cell binding by the endogenous chemokines or small molecule antagonists, for CCR2, CCR5 and the chimeric receptors expressed in COS-7 cells. The chemokine radioligand that was used for each construct is indicated in the first column.

Radioligand - Construct	endogenous ligands (CCL2 or CCL3)		orthosteric INCB3344	allosteric CCR2-RA-[R]		allosteric JNJ-27141491		allosteric SD-24	
	pIC <sub>50</sub> ± S.E.M. and (IC <sub>50</sub> (nM))								
<sup>125</sup> I-CCL2 - CCR2	9.7 ± 0.2 <sup>a</sup>	(0.21)	7.8 ± 0.2	(16)	6.1 ± 0.1	(746)	6.6 ± 0.1	(241)	< 5
<sup>125</sup> I-CCL3 - CCR5	8.7 ± 0.4 <sup>b</sup>	(1.9)	5.3 ± 0.2	(4508)	< 5		5.4 ± 0.1	(4254)	no displacement
<sup>125</sup> I-CCL2 - CCR5- CCR2(all)	8.9 ± 0.3 <sup>a</sup>	(1.3)	6.3 ± 0.1**	(516)	< 5		5.0 ± 0.1*	(10650)	no displacement
<sup>125</sup> I-CCL3 - CCR5- CCR2(C-term)	8.9 ± 0.2 <sup>b</sup>	(1.4)	no displacement		5.1 ± 0.1	(7638)	< 5		no displacement
<sup>125</sup> I-CCL2 - CCR2- CCR5(C-term)	8.9 ± 0.2 <sup>a</sup>	(1.4)	7.3 ± 0.1	(48)	5.7 ± 0.2	(1908)	6.4 ± 0.1	(364)	< 5

Data are presented as mean pIC<sub>50</sub> ± S.E.M. and mean IC<sub>50</sub> (nM) of at least three experiments performed in duplicate.

<sup>a</sup> pIC<sub>50</sub> of CCL2.

<sup>b</sup> pIC<sub>50</sub> of CCL3.

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\*  $p < 0.05$  vs. CCR5, Student's t-test.

\*\*  $p < 0.005$  vs. CCR5, Student's t-test.



**Table 2.** IP turnover activation by chemokines and inhibition by small molecule antagonists for CCR2, CCR5 and the chimeric receptors expressed in COS-7 cells. In case of the assays with the antagonists, a chemokine concentration that evoked 80% of the maximum response ( $EC_{80}$ ) was used. The chemokine that was used for each construct is indicated in the first column.

Chemokine - Construct	endogenous ligands (CCL2 or CCL3)	orthosteric INCB3344	allosteric CCR2-RA-[R]	allosteric JNJ-27141491	allosteric SD-24
	$pEC_{50} \pm S.E.M.$ and ( $EC_{50}$ (nM))	$pIC_{50} \pm S.E.M.$ and ( $IC_{50}$ (nM))			
CCL2 - CCR2	9.2 ± 0.3 (0.63)	8.0 ± 0.01 (10)	7.0 ± 0.1 (93)	7.1 ± 0.1 (85)	6.6 ± 0.3 (236)
CCL3 - CCR5	8.1 ± 0.2 (8.0)	5.3 ± 0.01 (4645)	6.2 ± 0.1 (680)	5.9 ± 0.1 (1201)	5.3 ± 0.1 (5206)
CCL2 - CCR5-CCR2(all)	9.4 ± 0.3 (0.41)	7.0 ± 0.4* (104)	5.2 ± 0.2** (6227)	5.4 ± 0.2 (3837)	5.2 ± 0.1 (6133)
CCL3 - CCR5-CCR2(C-term)	8.1 ± 0.3 (7.4)	5.4 ± 0.1 (4399)	6.4 ± 0.1 (428)	5.6 ± 0.2 (2605)	5.6 ± 0.1* (2301)
CCL2 - CCR2-CCR5(C-term)	9.3 ± 0.2 (0.48)	7.8 ± 0.2 (18)	6.9 ± 0.2 (126)	6.9 ± 0.1 (121)	6.4 ± 0.2 (388)

Data are presented as mean  $pEC_{50} \pm S.E.M.$  and  $pIC_{50} \pm S.E.M.$  as well as mean  $EC_{50}$  (nM) and mean  $IC_{50}$  (nM) of at least three experiments performed in duplicate.

\*  $p < 0.05$  vs. CCR5, Student's t-test.

\*\*  $p < 0.005$  vs. CCR5, Student's t-test.

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**Table 3.** Displacement of [<sup>3</sup>H]-INCB3344 binding and [<sup>3</sup>H]-CCR2-RA binding from CHO membranes expressing FLAG-tagged CCR2, CCR5 and CCR2-CCR5(C-term) receptors.

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	<b>[<sup>3</sup>H]-INCB3344</b>		<b>[<sup>3</sup>H]-CCR2-RA</b>	
<b>Construct</b>	<b>pK<sub>D</sub> ± S.E.M. and (K<sub>D</sub> (nM))</b>			
CCR2	8.1 ± 0.1	(8.3)	8.8 ± 0.1	(1.7)
CCR5	no binding		7.0 ± 0.1	(100)
CCR2-CCR5(C-term)	8.6 ± 0.1	(2.3)	8.7 ± 0.1	(2.0)

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Data are presented as mean pK<sub>D</sub> ± S.E.M. or mean K<sub>D</sub> (nM) of at least three experiments performed in duplicate.

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**Table 4.** Displacement of [<sup>3</sup>H]-INCB3344 binding and [<sup>3</sup>H]-CCR2-RA binding from CHO membranes expressing HA-tagged WT and mutant CCR2 receptors.

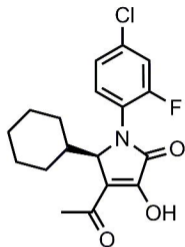
Construct	[ <sup>3</sup> H]-INCB3344 displacement by INCB3344		[ <sup>3</sup> H]-CCR2-RA displacement by CCR2-RA-[R]	
	pIC <sub>50</sub> ± S.E.M. and IC <sub>50</sub> (nM)			
WT CCR2	7.8 ± 0.03	(16)	7.8 ± 0.05	(16)
K72A <sup>2,34</sup>	7.8 ± 0.01	(15)	7.7 ± 0.1	(21)
D78N <sup>2,40</sup>	7.8 ± 0.1	(16)	7.7 ± 0.1	(21)
I208A <sup>5,45</sup>	7.8 ± 0.1	(17)	7.7 ± 0.1	(19)
V244A <sup>6,36</sup>	8.1 ± 0.03*	(7.5)	no binding	
E291A <sup>7,39</sup>	6.9 ± 0.1*	(126)	7.7 ± 0.1	(21)
Y305A <sup>7,53</sup>	7.7 ± 0.03	(19)	no binding	
K311A <sup>8,49</sup>	7.7 ± 0.03	(18)	6.8 ± 0.1*	(169)
F312A <sup>8,50</sup>	8.0 ± 0.1*	(9.2)	no binding	

Data are presented as mean pIC<sub>50</sub> ± S.E.M. and mean IC<sub>50</sub> (nM) of at least three experiments performed in duplicate.

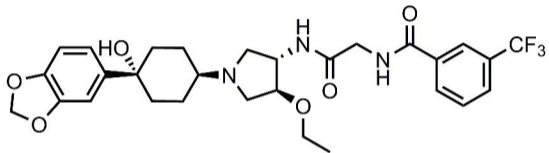
ND, not determined

\* p < 0.005 vs. WT CCR2, Student's t-test.

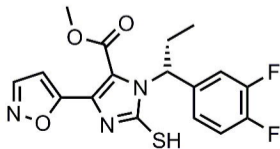
# Figure 1



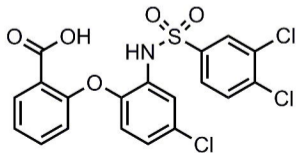
CCR2-RA-[R]



INCB3344

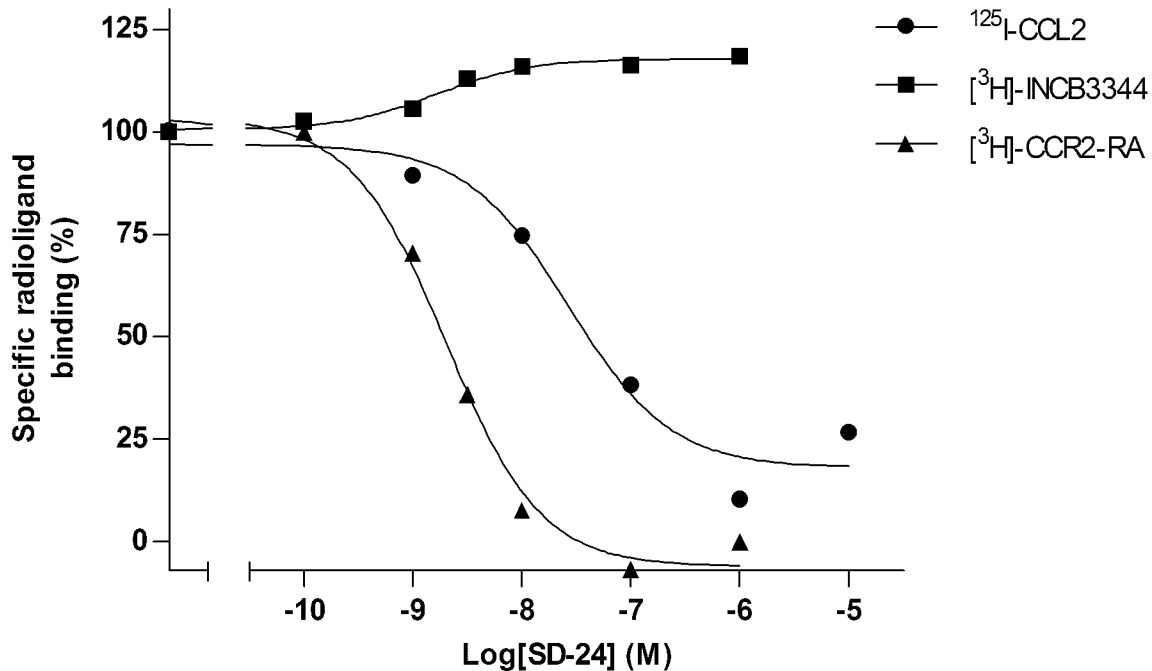


JNJ-27141491



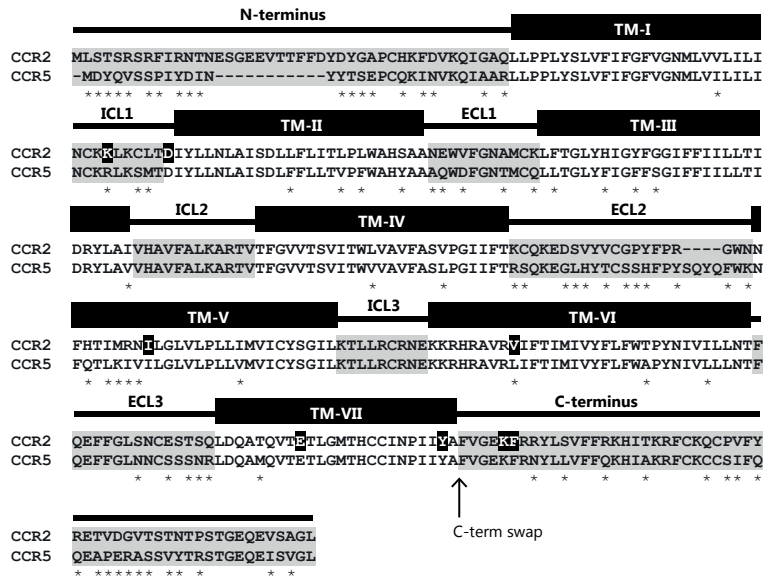
SD-24

# Figure 2

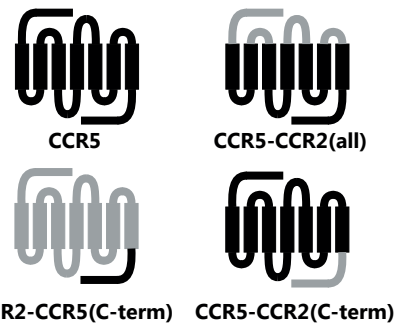


# Figure 3

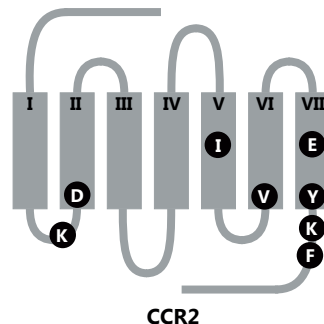
## A



## B

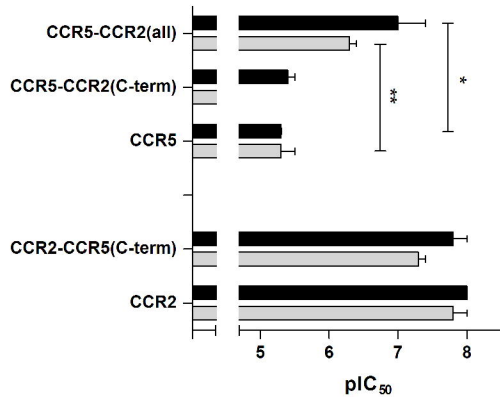


## C

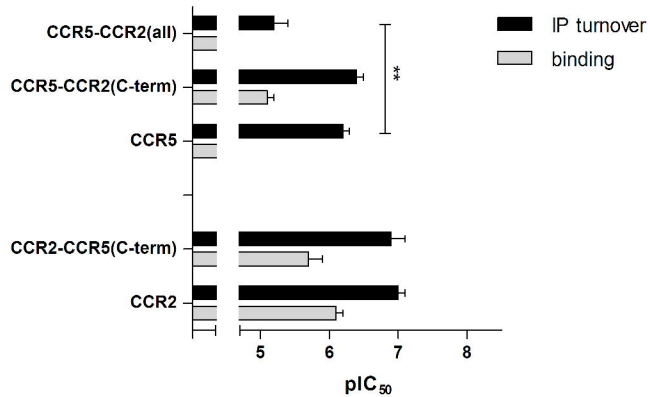


# Figure 4

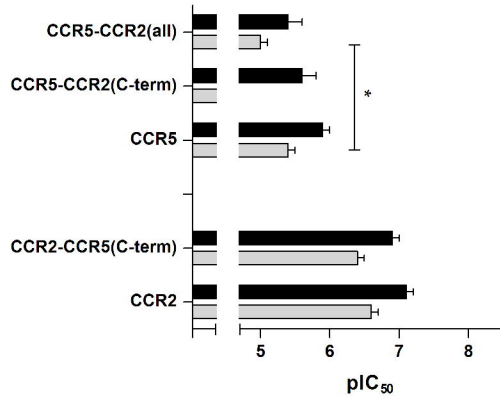
## INCB3344



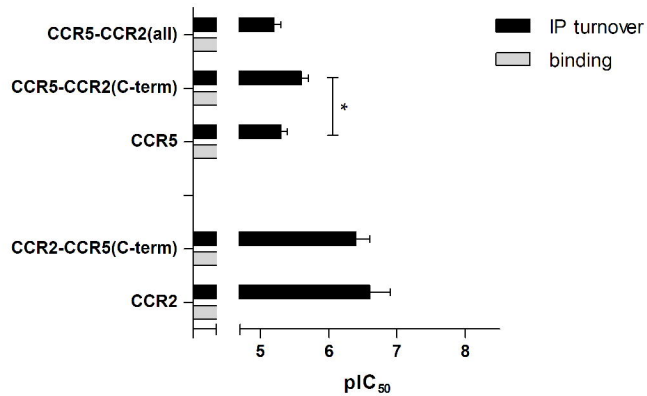
## CCR2-RA-[R]



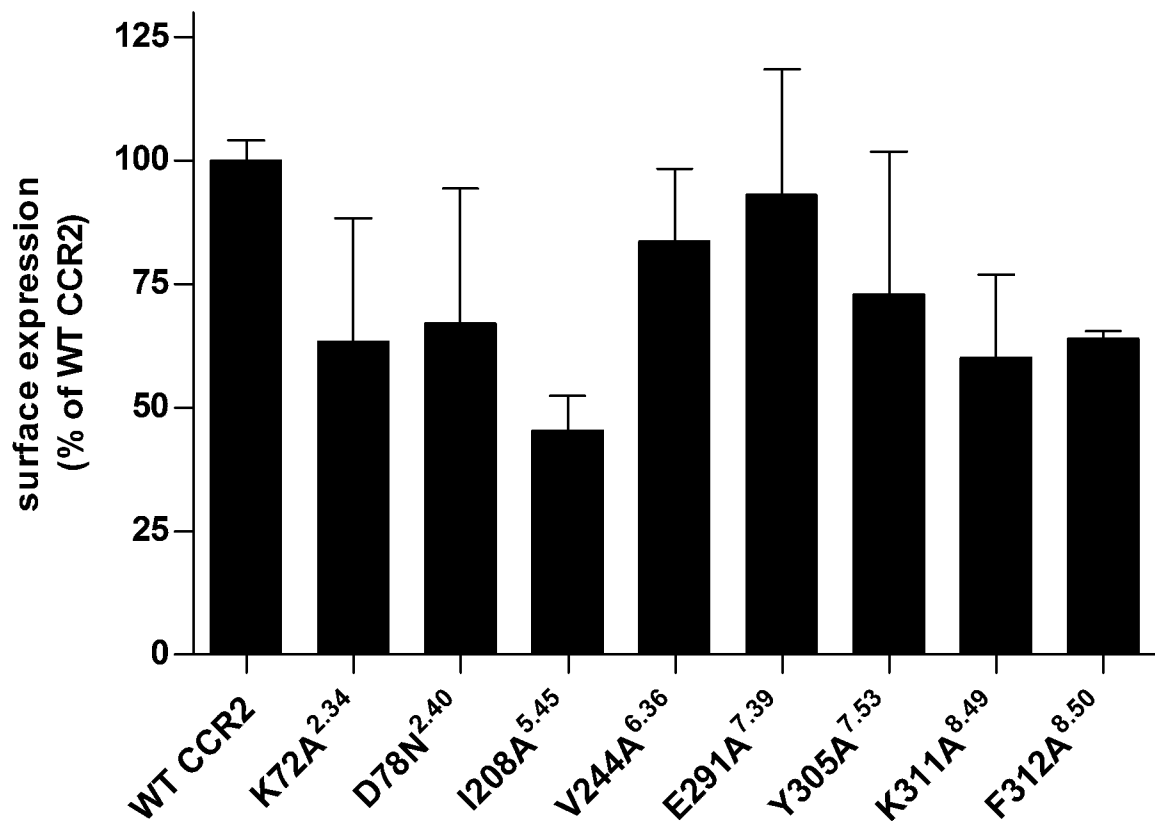
## JNJ-27141491



## SD-24

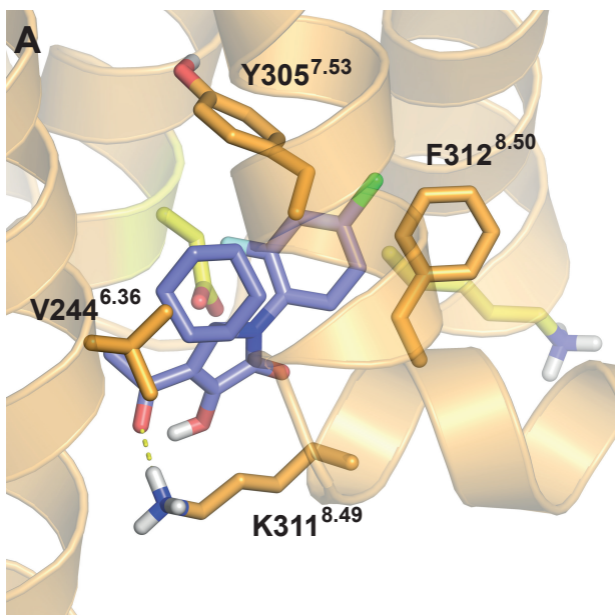


# Figure 5

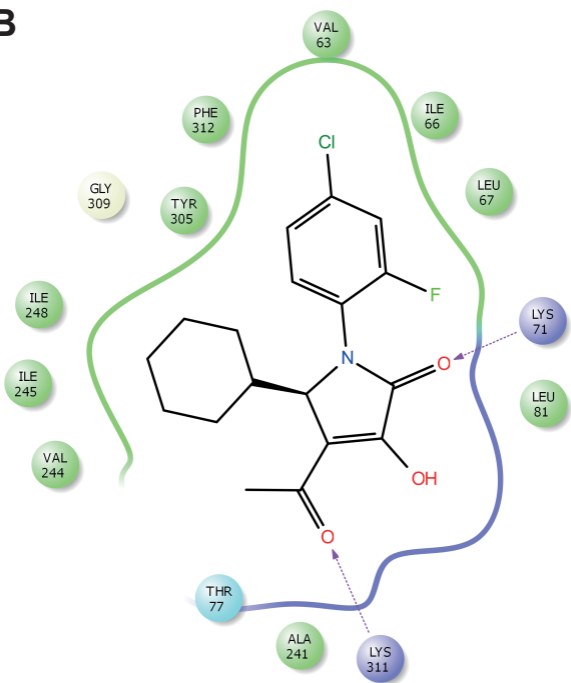




# Figure 6



**B**



# Figure 7

