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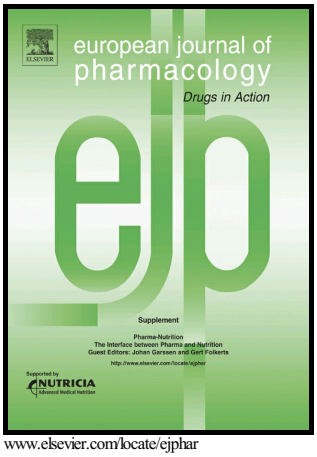

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Serotonin 2A receptor disulfide bridge integrity is crucial for ligand binding to different signalling states but not for its homodimerization

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Abstract

The serotonin 2_A (5-HT_{2A}) receptor is a G-protein coupled receptor (GPCR) with a conserved disulfide bridge formed by Cys^{148} (transmembrane helix 3, TM3) and Cys^{227} (extracellular loop 2, ECL-2). We hypothesized that disulfide bridges may determine serotonin 5-HT_{2A} receptor functions such as receptor activation, functional selectivity and ligand recognition. We used the reducing agent dithiothreitol (DTT) to determine how the reduction of disulfide bridges affects radioligand binding, second messenger mobilization and receptor dimerization. A DTT-induced decrease in the number of binding sites (1190 ± 63.55 fmol/mg protein for control cells compared with 921.2 ± 60.84 fmol/mg protein for DTT-treated cells) as well as in the efficacy of both signalling pathways characterized was observed, although

the affinity and potency were unchanged. Bioluminiscence resonance energy transfer (BRET) assays revealed the DTT treatment did not modify the homodimeric nature of serotonin 5-HT_{2A} receptors. In molecular dynamic simulations, the ECL-2 of the receptor with a broken cysteine bond adopts a wider variety of conformations, some of which protrude deeper into the receptor orthosteric binding pocket leading to collapse of the pocket. A shrunken binding pocket would be incapable of accommodating lysergic acid diethylamide (LSD). Our findings suggest that the decrease of efficacy may be due to disruption of disulfide bridge between TM3 and ECL-2. This reveals the integrity of the ECL-2 epitope, which should be explored in the development of novel ligands acting as allosteric modulators of serotonin 5-HT_{2A} receptors.

Keywords: serotonin 2_A receptor, phospholipase A_2, phospholipase C, radioligand binding, disulfide bridges, dithiothreitol

Chemical compounds studied in this article

DL-1,4-Dithiothreitol (PubChem CID: 446094); Serotonin hydrochloride (PubChem CID: 160436); Clozapine (PubChem CID: 2818); Methysergide maleate (PubChem CID: 5281073); [^{3}H]LSD (PubChem CID: 44559100)

1. Introduction

G-protein coupled receptors (GPCRs) can modulate a wide range of physiological processes being involved in numerous diseases. All GPCRs share a common structure, including an extracellular N-terminus, seven-α-helix transmembrane regions connected by three alternating extracellular loops (ECL1-3), three intracellular loops (ICL1-3) and an intracellular C-terminus. A disulfide bond connecting the ECL-2 and the top of transmembrane (TM) helix 3 is found in >90% of all GPCRs and has been suggested to be important for receptor conformation, ligand recognition and functioning (Angers et al., 2002; Kclo et al., 2005; Park et al., 2004; Rios et al., 2001; Venkatakrishnan et al., 2013; Wheatley et al., 2012, 2007). Other disulfide bonds in the extracellular side have been described for different receptors (Storjohann et al., 2008).

The serotonin 2_A receptor (5-HT_{2A}) is a class A GPCR associated with schizophrenia as an important target for atypical antipsychotic drugs (González-Maeso et al., 2008; Roth et al., 1998). This receptor was one of the first types of GPCR for which the functional selectivity phenomenon was observed, with different ligands differentially activating phospholipase A_2 (PLA_2) - inducing arachidonic acid (AA) release - and phospholipase C (PLC) - resulting in the production of inositol phosphate (IP) formation and diacylglycerol (DAG) - for the same receptor (Berg et al., 1998; Felder et al., 1990; Hoyer et al., 1994; Urban et al., 2007).

We have previously demonstrated the existence of 5-HT_{2A} homo-oligomers in the human brain and in recombinant cell lines, moreover a negative cooperativity phenomenon for certain ligands was observed, such as clozapine, through the PLA_2 signalling pathway (Albizu et al., 2006; Brea et al., 2009; Iglesias et al., 2016).

Recent reports indicate that lysergic acid diethylamide (LSD) displays slow binding kinetics at serotonin 5-HT_{2A} and 5-HT_{2B} receptors. In view of the 5-HT_{2B} crystal structure, it has been

proposed that this may be due to a lid formed by ECL-2 at the entrance to the binding pocket (Wacker et al., 2017).

From a structural viewpoint, the serotonin 5-HT_{2A} receptor contains a total of fifteen cysteines, seven on the extracellular side and one at the top of TM3. The GPCR conserved disulfide bridge is formed by Cys^{148} (TM3) and Cys^{227} (ECL-2) (**Fig. 1**). We hypothesized that this disulfide bridge may determine serotonin 5-HT_{2A} receptor functions such as receptor activation, functional selectivity and ligand recognition.

There were several studies disrupting the conserved disulfide bond in different GPCRs by mutagenesis studies, but it has been described that mutant receptors were restricted to endoplasmic reticulum showing lower membrane expression (Barington et al., 2016; Conner et al., 2007; Rummel et al., 2013; Scholl and Wells, 2000), thus the effect of disulfide bridges on ligand binding or function can be masked by the effect due to the mutation itself.

The aim of this study was to characterize the effect of the reduction in the number of disulfide bridges in serotonin 5-HT_{2A} receptor by employing the solvent accessible reducing agent dithiothreitol (DTT). This allows disrupting the disulfide bridges while keeping the primary structure of serotonin 5-HT_{2A} receptors.

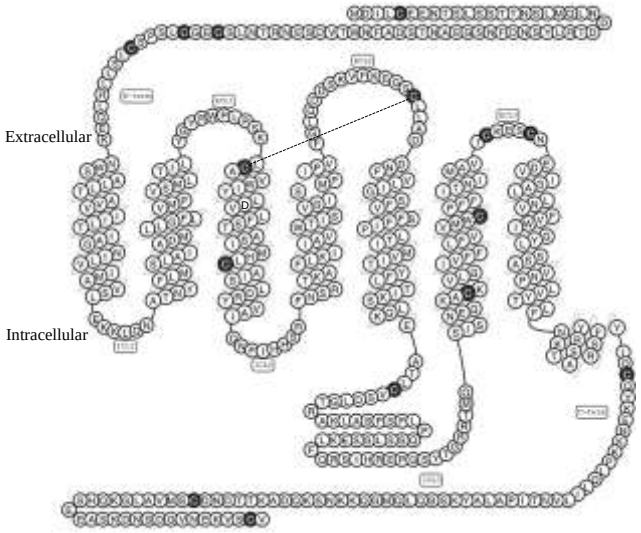

Fig. 1. A secondary structure model of the human serotonin 5-HT_{2A} receptor. The location of 15 cysteine residues (black circles) and the conserved disulfide bridge are indicated (modified from www.gpcrdb.org).

2. Material and Methods

2.1. Drugs and reagents

[^{3}H]LSD (83.6 Ci/mmol), [^{3}H]*myo*-Inositol (20.3 Ci/mmol) and [^{14}C]arachidonic acid (57.1 mCi/mmol) were purchased from PerkinElmer Life Science (Waltham, Massachusetts). DTT**,** clozapine, methysergide maleate and serotonin hydrochloride (5-HT) were purchased from Sigma Aldrich (St. Louis, Missouri). RNA Binding YSi SPA Beads and OptiPhase Supermix scintillation cocktail were purchased from Perkin Elmer (Waltham, Massachusetts). Bovine Serum Albumin (BSA) Fraction V fatty acid free was purchased from Roche (Basel, Switzerland). MultiScreen® Filter Plates were purchased from Millipore (Billerica, Massachusetts). All other reagents were purchased from Sigma Aldrich.

2.2. Cell culture

Cells were grown at 37 ºC in a 5% CO_2 humidified atmosphere. Chinese hamster ovary (CHO) cells stably expressing human serotonin 5-HT_{2A} receptors at a density of~200 fmol/mg protein (CHO-FA4 cells, passages between 12 and 25) were maintained in standard tissue culture plates (150 mm in diameter) in Dulbecco's Modified Eagle's Medium-F12 (DMEM-F12; Gibco) supplemented with 10% (v/v) foetal bovine serum (FBS; Sigma Aldrich), 1% L-glutamine (Sigma Aldrich), 100 U/ml penicillin/0.1mg/ml streptomycin (Sigma Aldrich) and 300 μg/ml hygromycin (Invitrogen).

Human Embryonic Kidney 293T cells (HEK 293T) (passages between 10 and 18) were maintained in standard tissue culture plates (150 mm in diameter) in Dulbecco's Modified Eagle's Medium (DMEM; Sigma Aldrich) supplemented with 10% (v/v) FBS, 1% (v/v) Glutamax (Gibco) and 100 U/ml penicillin/0.1 mg/ml streptomycin.

2.3. Membrane preparations of human serotonin 5-HT_{2A} receptors

Prior to being harvested, stably transfected cells were grown for 24 h in DMEM-F12 supplemented with 10% (v/v) dialyzed FBS without hygromycin. The culture medium was

aspirated and the cells were washed twice with ice-cold phosphate buffered saline (PBS) before being scraped from the culture plate in PBS and pelleted by centrifugation at 800 x *g*, 15 min at 4 ºC. The cell pellet was resuspended in PBS or PBS supplemented with 20 mM DTT and incubated for 10 min at 37 ºC. The cell suspension was then centrifuged under the same conditions. The cell pellet was washed in ice-cold PBS, resuspended in 50 mM Tris-HCl, pH= 7.5 at 4 ºC, and homogenized with a Polytron homogenizer. The homogenate was centrifuged at 48000 x *g* for 40 min at 4 ºC and the resulting pellet was resuspended in 50 mM Tris-HCl, pH= 7.5, at 4ºC. The protein concentration was determined by the Bradford method with the Bio-Rad Protein Assay (Bio-Rad, California) and bovine serum albumin as standard.

2.4. Saturation binding assays with human serotonin 5-HT$_{2A}$ receptors

Membranes obtained from CHO-FA4 expressing serotonin 5-HT$_{2A}$ receptors prepared either in the absence or presence of 20 mM DTT were incubated with eight different concentrations of [^{3}H]LSD (83.6 Ci/mmol) in the range 0.16-20 nM (80 µg of protein per well) in the incubation buffer (50 mM Tris-HCl, pH= 7.5). Non-specific binding was determined by the addition of 1 µM methysergide. The reaction mixture was incubated at 37 °C for 30 min. The reaction samples were transferred to a multiscreen GF/B 96-well plate (Millipore) pretreated with 0.5% polyethylenimine (PEI, Sigma Aldrich) and were then filtered and washed six times with 250 µl wash buffer (50 mM Tris-HCl, pH 6.6). The filters were dried and 30 µl Universol (MP Biomedicals, Santa Ana, California) was added to each well. The radioactivity was detected in a microplate beta scintillation counter (Microbeta Trilux, PerkinElmer).

2.5. Binding kinetics: determination of association and dissociation rates

Membranes obtained from CHO-FA4 expressing serotonin 5-HT$_{2A}$ receptors prepared either in the absence or presence of 20 mM DTT were incubated in 50 mM Tris-HCl (pH 7.5) and 1 nM [^{3}H]LSD (83.6 Ci/mmol) in a 96 well plate (80 µg of protein per well) at 37 ºC. Association was measured at different times between 0 and 60 minutes, and dissociation was

initiated 30 minutes later by addition of 1 μM methysergide at different times between 0 and 180 minutes. Non-specific binding was measured in the presence of 1 μM methysergide. Samples were transferred to a multiscreen GF/B 96-well plate pretreated with 0.5% PEI and the subsequent procedure was the same as described in saturation binding assays section.

2.6. Competition binding to human serotonin 5-HT_{2A} receptors

Serotonin 5-HT_{2A} receptor competition binding experiments were carried out with membranes from CHO-5-HT_{2A} cells that were either pretreated or not pretreated with 20 mM DTT (in the preparation protocol). On the day of the assay, membranes were defrosted and resuspended in incubation buffer (50 mM Tris-HCl, pH 7.5). Each reaction well of a 96-well plate contained 80 μg of protein, 1 nM [^{3}H]LSD (83.6 Ci/mmol) and different concentrations of clozapine. Non-specific binding was determined in the presence of 1 μM methysergide. The reaction mixture was incubated at 37 °C for 30 min. Samples were transferred to a multiscreen GF/B 96-well plate pretreated with 0.5% PEI and the subsequent procedure was the same as described in saturation binding assays section.

2.7. Measurement of effect of treatment with 20 mM DTT on AA release and IP accumulation in CHO-FA4 cells expressing human serotonin 5-HT_{2A} receptors

Measurement of AA release and IP accumulation was performed simultaneously in the same well, as previously described (Iglesias et al., 2016).

Cells were seeded into 96-well tissue culture plates at a density of $2x10^4$ cells/well. After 24 h, the medium was replaced with serum-free medium containing 10 μCi/ml [^{3}H]*myo*-inositol (20.3 Ci/mmol) for 24 h and 0.2 μCi/ml [^{14}C]arachidonic acid (57.1 mCi/mmol) for 4 h at 37 ºC.

After the labelling period, control cells were washed for 10 min at 37 ºC with Hanks' Balanced Salt Solution (HBSS, Sigma Aldrich) supplemented with 20 mM HEPES, 20 mM LiCl and 2% fatty acid free BSA (experimental medium). Treated cells were washed with

experimental medium supplemented with 20 mM DTT. The cells were then incubated for 20 min with experimental medium at 37 ºC containing vehicle or the indicated concentrations of drugs (clozapine and 5-HT). At the end of the incubation time, 90 µl of medium was added to the flexiplate with 150 µl OptiPhase SuperMix cocktail for measurement of [^{14}C]AA release. The medium was discarded and 200 µl of 100 mM formic acid was added to the cells for 30 min at 4ºC, then 20 µl were added to the flexiplate with 80 µl of a solution of RNA Binding YSi SPA beads for measurement of the accumulation of [^{3}H]IPs from the cells (IP_1, IP_2, and IP_3, collectively referred to as IPs). The radioactivity was quantified with a liquid scintillation counter (WALLAC Microbeta TriLux 1450-023).

2.8. Bioluminiscence resonance energy transfer (BRET) assays for assessment of receptor dimerization

BRET methodology is based on the fact that the degree of physical proximity (< 100 Å) between molecules can be assessed in living cells by the level of energy transfer between the energy donor *Renilla* luciferase (RLuc) and a fluorescence acceptor, the yellow fluorescence protein (YFP). BRET saturation experiments were performed using HEK293T cells previously seeded into 100-mm dishes at a density of 2x10^6 cells and transfected 24 h later with a fixed amount of RLuc-N2-5-HT_{2A} luciferase donor plasmid (0.06 µg DNA/dish) and with increasing amounts of pcDNA3-5-HT_{2A}-YFP acceptor plasmid (from 0.06 to 4 µg DNA/dish) by using linear polyethylenimine MW-25000 at a DNA/polyethylenimine ratio of 1:6 (Jenkins et al., 2010). In each transfection mix, the total amount of DNA was maintained constant by the addition of empty vector up to 5 µg. The transfection medium was aspirated 24 hours after transfection. The cells were then washed with PBS and 5x10^4 cells/well were seeded in a 96-well plate pretreated with 0.1 mg/ml poly-D-lysine hydrobromide (Sigma Aldrich). Forty-eight hours post transfection, the cells were washed with HBSS and incubated with HBSS or HBSS supplemented with 20 mM DTT for 10 min at 37 ºC. The YFP

expression was then quantified in each well by direct measurement of fluorescence emission at 530 nm (excitation wavelength of 480 nm). The buffer was removed and coelenterazine *h* (Molecular Probes) was added to a final concentration of 5 μM in HBSS. The plate was incubated for 10 min at 37 ºC in darkness and BRET was subsequently quantified by dual bioluminescence measurement (370-480 nm for RLuc emission and 520-570 nm for YFP emission). Ten minutes later, total luminescence (400-700 nm) was quantified as a measure of donor expression. All measurements were performed in an Infinite® M1000Pro (TECAN) microplate reader. The BRET ratio was calculated as emission at 520-570 nm/emission at 370-480 nm. Net BRET was defined as the 530 nm/485 nm ratio of cells co-expressing donor (RLuc) and acceptor (YFP) plasmid constructs minus the BRET ratio of cells expressing only the donor (RLuc) plasmid construct in the same experiment. Results were expressed as milli net BRET units (mBU), which correspond to the net BRET ratio values multiplied by 1000. BRET saturation curves were obtained by representing mBU as a function of the acceptor expression/donor expression, as determined by direct quantification of fluorescence and total luminescence emission. Data were fitted to the hyperbolic function (one binding site) with GraphPad Prism 4.0 software. The equation parameters maximum number of binding sites (B_{max}) and equilibrium dissociation constant (K_d) corresponded respectively to the maximal BRET signal obtained ($BRET_{max}$) and $BRET_{50}$, i.e. the acceptor/donor ratio providing 50% of the $BRET_{max}$.

2.9. In silico structural model of ECL-2 on human serotonin 5-HT$_{2A}$ receptor before and after disruption of the Cys^{148}-bond

In order to build a serotonin 5-HT_{2A} receptor model, we used the recently determined structure of the related serotonin 5-HT_{2B} receptor in complex with LSD (PDB ID 5TVN) as template. We first aligned the Uniprot sequence of the serotonin 5-HT_{2A} receptor to the one of the serotonin 5-HT_{2B} receptors with MOE software (Molecular Operating Environment

(MOE) software, http://www.chemcomp.com/ software.htm). We then built a homology model and optimized the model with the AMBER12:EHT force field included in the MOE software (Case et al., 2012). Finally, the model was stereochemically validated with PROCHECK (Laskowski et al., 1993).

In order to evaluate the conformational space of the ECL-2 with an intact and broken cysteine bond, we explored both conditions by performing a Low Mode Search analysis of this region with MOE software (with the AMBER12:EHT force field, Born solvation and a temperature of 300 K). The following conditions were applied for the Low Mode Search: rejection limit of 100, iteration limit of 500, RMSD gradient of 0.1 and maximum number of energy minimization iterations of 500. The tolerance for equal conformations was set to a RMSD of 1, while the energy window was set to 100. Using these settings, we obtained 495 conformations for the receptor with a broken disulfide bridge and 490 different conformations for the receptor with an intact disulfide bridge. From this pool of conformations, we selected the best 200 conformations in terms of energy and depicted them by a stride of 2 in **Figure 8**.

2.10. Data analysis

Nonlinear fitting of the concentration-response curves was conducted with Prism 4.0 software (GraphPad Software, La Jolla, USA) by applying both a four-parameter logistic equation and a two-site competition equation. Dissociation and association kinetic data were fitted to a one-phase exponential decay equation and a one-phase exponential association equation, respectively. Statistical comparisons between fits were performed by extra sum-of-squares *F* test (Giraldo et al., 2002). Statistical significance was set at $P < 0.05$. Statistical comparisons between binding and functional parameters (treated relative to control) were performed by Student's *t*-test with SPSS statistics 20 (IBM). Statistical significance was set at $P < 0.05$. The association rate constant (k_{on}) was calculated by using the following equation:

$$k_{on} = \frac{k_{ob} - k_{off}}{[radioligand(nM)]}$$

where k_{obs} is the observed association rate constant and k_{off} the dissociation rate constant (k_{off}).

3. Results

3.1. Treatment of human serotonin 5-HT$_{2A}$ receptors with DTT modified ligand binding properties

To investigate the effect of DTT on ligand binding properties of the serotonin 5-HT$_{2A}$ receptor, radioligand binding assays (saturation, kinetic and competition assays) were conducted with [^{3}H]LSD in the presence and absence of 20 mM DTT. Representative saturation isotherms for serotonin 5-HT$_{2A}$ receptor, with either buffer or DTT treatment, are shown in **Figure 2**. DTT treatment induced a statistically significant decrease in B_{max} ($P < 0.05$, Student's unpaired *t* test) without affecting the K_d value (**Fig 2**; **Table 1**).

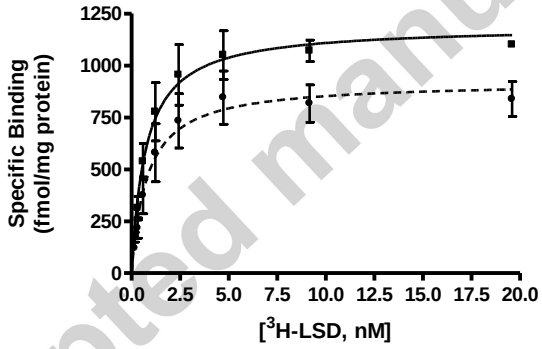

Fig. 2. Saturation binding curve for [^{3}H]LSD in CHO-FA4 cells expressing human serotonin 5-HT$_{2A}$ receptors. The solid line represents the control and the dashed line represents the 20 mM DTT treatment. The points represent the mean ± S.E.M (vertical bars) values of three independent experiments (n=3) performed with triplicate measurements.

Table 1

Effect of DTT on binding capacity and affinity of [^{3}H]LSD on human serotonin 5-HT$_{2A}$ receptor transfected in CHO-FA4 cells.

	Binding Saturation	
	B_{max} (fmol/mg protein)	K_d (nM)
Control	1190 ± 63.55	0.73 ± 0.14
20 mM DTT Treated	921.2 ± 60.84[a]	0.80 ± 0.21

The values represent mean ± S.E.M of three independent experiments each performed in triplicate.
[a] indicates $P < 0.05$ treated versus control cells (Student's unpaired *t* test).

Kinetic analysis of [^{3}H]LSD binding revealed statistically significant differences in the percentage of specific binding in association experiments in which a decrease of 40.54% in cells treated with DTT was observed ($P < 0.05$, Student's unpaired *t* test). k_{on} and association half time ($t_{1/2}$) remained unaltered relative to the control (**Fig. 3A**; **Table 2**). In the dissociation experiments, no change in k_{off} was observed. The residence times of LSD (calculated as 1/ k_{off}) were 78.3 min for control and 57.2 min for DTT-treated cells. The K_d value calculated from k_{off}/k_{on} ratio for DTT treatment was similar to that observed in saturation experiments, while the dissociation constant calculated for control was slightly lower than the observed in saturation experiments, but no significant differences were observed (**Fig. 3B**; **Table 2**).

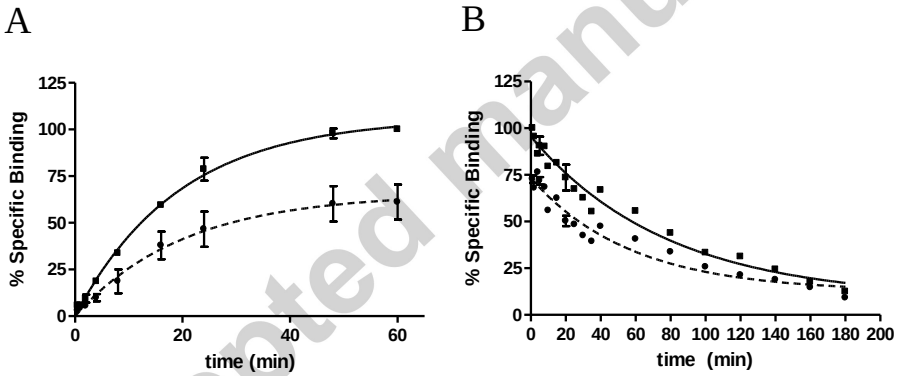

Fig. 3. Specific binding of [^{3}H]LSD to the human serotonin 5-HT$_{2A}$ receptor in membranes of CHO 5-HT$_{2A}$ cells treated (dashed line) and untreated with DTT (continuous line), measured in association (A) or dissociation assays (B). Non-specific binding was evaluated in presence of 1 μM methysergide. The points represent the mean ± S.E.M (vertical bars) of three independent experiments (n=3) performed with triplicate measurements.

Table 2

Kinetic parameters for [^{3}H]LSD binding to human serotonin 5-HT$_{2A}$ receptor at 37 ºC.

	Binding Kinetics					
	% Specific Binding (association assays)	k_{on} ($nM^{-1}min^{-1}$)	$t_{1/2}$ association (min)	k_{off} (min^{-1})	$t_{1/2}$ dissociation (min)	K_d calculated (k_{off}/k_{on}, nM)
Control	106.2 ± 2.51	0.033	14.00	0.01277	54.26	0.382
20 mM DTT treated	65.66 ± 5.77[a]	0.027	14.89	0.01748	39.65	0.639

The values represent the mean of three independent experiments each performed in triplicate.
[a] indicates $P < 0.05$ treated versus control cells (Student's unpaired *t* test).

In order to test the effects of DTT on antagonist binding, we carried out competition binding assays with clozapine and [^{3}H]LSD as a radioligand in membranes of CHO-5-HT_{2A} cells treated or not treated with 20 mM DTT. Total specific binding decreased by 29.39 % for cells treated with DTT ($P < 0.001$, Student's unpaired *t* test), but neither clozapine inhibition constant (K_i) nor affinity changed when compared to untreated cells (**Fig. 4**; **Table 3**)

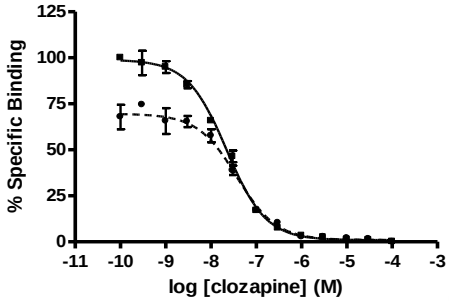

Fig. 4. [^{3}H]LSD binding displacement curves for clozapine at human serotonin 5-HT_{2A} receptors. The solid line represents the control and the dashed line represent cells treated with 20 mM DTT. The points represent the mean ± S.E.M (vertical bars) of four independent experiments (n=4) performed with duplicate measurements.

Table 3

Effect of DTT on competition parameters of clozapine at human serotonin 5-HT_{2A} receptors.

	Binding Competition	
	% Specific Binding	K_i (nM)
Control	98.95 ± 1.27	11.34 ± 0.71
20 mM DTT treated	69.56 ± 1.88[a]	19.11 ± 2.76

The values represent the mean ± S.E.M of at least four independent experiments each performed in duplicate.
[a] indicates $P < 0.001$ treated versus control cells (Student's unpaired *t* test).

3.2. Treatment with DTT modified the activation of human serotonin 5-HT$_{2A}$ receptors: quantification of AA release and IP accumulation.

To assess the effect of DTT on receptor functionality, concentration-response curves of 5-HT -induced IP accumulation in the absence and presence of 20 mM DTT were constructed.

When IP accumulation was measured, the 5-HT decrease by 25.36% in the maximal response (E_{max}) for cells treated with DTT (%E_{max} of 98.82 ± 2.75 for control cells and %E_{max} of 73.46 ± 2.39 for 20 mM DTT-treated cells) ($P < 0.001$, Student's unpaired *t* test). No significant differences in 5-HT potency were observed (pEC$_{50}$ of 6.25 ± 0.07 for control and pEC$_{50}$ of 6.08 ± 0.09 for 20mM DTT treated) (**Fig. 5**).

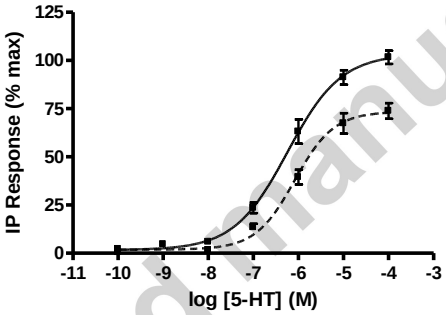

Fig. 5. Concentration-response curves of 5-HT on human serotonin 5-HT$_{2A}$ receptors induced IP accumulation. The solid line represents the control, the dashed line represents cells treated with 20 mM DTT. The points represent the mean ± S.E.M (vertical bars) of three independent experiments (n=3) performed with triplicate measurements.

Clozapine concentration-response curves were then constructed for the absence and presence of different concentrations of DTT (5, 20 and 40 mM). We previously observed that clozapine differentially modulates phospholipase A_2 and phospholipase C pathways coupled to serotonin 5-HT$_{2A}$ receptors: it inhibits 5-HT-induced stimulation of the PLA$_2$ pathway with a biphasic profile, while it inhibits the PLC pathway with a monophasic profile (Brea et al.,

2009; Iglesias et al., 2016). DTT treatment induced a statistically significant decrease of 1 μM 5-HT-induced activation in the two signalling pathways studied ($P < 0.001$, Student's unpaired *t* test) (**Fig. 6**; **Table 4** and **Table 5**), but no significant differences in the pIC_{50} values for either signalling pathway were observed relative to the control.

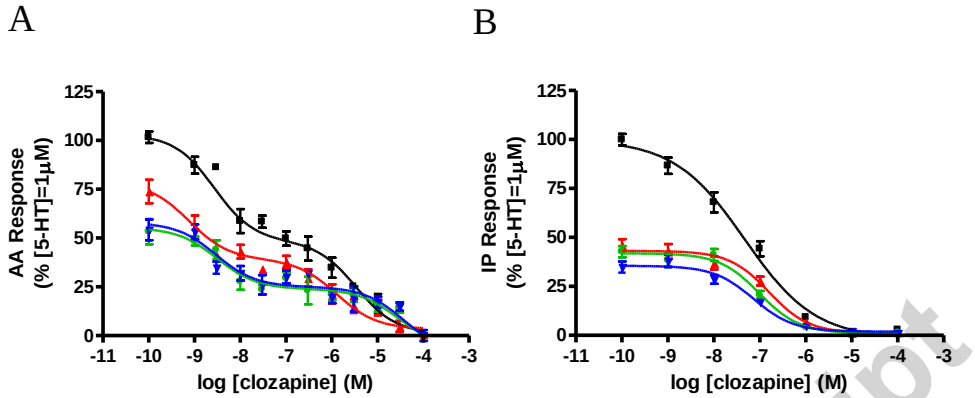

Fig. 6. (A) Concentration-response curves for clozapine on human serotonin 5-HT_{2A} receptors stimulated with 1 μM 5-HT and measurement of AA release. (B) Concentration-response curves for clozapine on human serotonin 5-HT_{2A} receptors stimulated with 1 μM 5-HT and measurement of IP accumulation. The black lines represent the control, the red lines represent cells treated with 5 mM DTT, the green lines represent cells treated with 20 mM DTT and the blue lines represent cells treated with 40 mM DTT. Points represent mean ± S.E.M (vertical bars) of independent experiments performed with triplicate measurements, *n*=7 for AA release and *n*=13 for IP accumulation.

Table 4

Effect of DTT on clozapine potency (pIC_{50}) and percentage of the effect elicited by 1 μM 5-HT in cells expressing human serotonin 5-HT_{2A} receptors for AA release.

	AA release	
	pIC_{50}	% E_{max} (1 μM 5-HT)
Control	8.56 ± 0.21 High; 5.46 ± 0.21 Low	103.10 ± 5.23
5 mM DTT treated	9.11 ± 0.27 High; 5.88 ± 0.22 Low	78.37 ± 6.67[a]
20 mM DTT treated	8.50 ± 0.23 High; 4.53 ± 0.37 Low	55.29 ± 3.81[a]
40 mM DTT treated	8.53 ± 0.24 High; 4.43 ± 0.40 Low	57.97 ± 4.44[a]

The values represent mean ± S.E.M of at least seven independent experiments each performed in triplicate.
[a] indicates $P < 0.001$ for treated versus control cells (Student's unpaired *t* test).

Table 5

Effect of DTT on clozapine potency (pIC_{50}) and percentage of the effect elicited by 1 μM 5-HT in cells expressing human serotonin 5-HT_{2A} receptors for IP accumulation.

	IPs accumulation	
	pIC_{50}	% E_{max} (1 μM 5-HT)
Control	7.32 ± 0.10	99.87 ± 4.07
5 mM DTT treated	6.80 ± 0.11	43.11 ± 1.50[a]
20 mM DTT treated	7.00 ± 0.10	41.88 ± 1.39[a]
40 mM DTT treated	7.13 ± 0.11	35.52 ± 1.29[a]

The values represent mean ± S.E.M of at least thirteen independent experiments each performed in triplicate.
[a] indicates $P < 0.001$ for treated versus control cells (Student's unpaired *t* test).

3.3. Treatment with DTT did not disrupt 5-HT_{2A} homodimers

To test the possible involvement of disulfide bonds in 5-HT_{2A} dimerization, we used BRET saturation assays to examine the effect of the reducing agent DTT on 5-HT_{2A} dimerization. HEK293T cells were co-transfected with a constant amount of RLuc-N2-5-HT_{2A} donor plasmid and increasing amounts of pcDNA3-5-HT_{2A}-YFP acceptor plasmid and they were treated or not treated (control) with DTT prior to determination of BRET efficacy. The results showed an increase in BRET signals as a function of increasing acceptor/donor expression in control cells that could be fitted to a rectangular hyperbolic function (**Fig. 7**). Neither the amplitude nor the shape of the BRET saturation curves were affected by DTT treatment (**Fig. 7**). The experiments performed yielded $BRET_{max}$ and $BRET_{50}$ values for the DTT-treated cells (mean ± S.E.M., n = 4) of 96.30 ± 4.086% and 110.0 ± 9.134 % of the values obtained for untreated cells, resulting in no statistically significant differences between both conditions (P = 0.4683 for $BRET_{max}$ and P = 0.2689 for $BRET_{50}$, Paired *t* test). This suggests that the possible effects of DTT on the integrity of cysteine-bonds do not alter the homodimerization state of the serotonin 5-HT_{2A} receptors in the transfected cells.

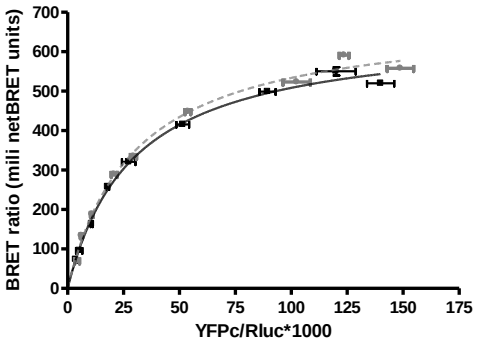

Fig. 7. BRET saturation curves for human serotonin 5-HT_{2A} receptors in transfected HEK293T cells. Cells were co-transfected with a fixed amount of RLuc-N2-5-HT_{2A} and increasing amounts of pcDNA3-5-HT_{2A}-YFP. The solid line represents untreated cells and the dashed line represents cells treated with 20 mM DTT. The graph shows the results (expressed as mean ± S.E.M.) of one representative experiment out of four, performed in quadruplicate. The R^2 values for the fitting were 0.9952 and 0.9924 for untreated and treated cells, respectively. $BRET_{max}$ values (mean ± S.E.M.) were 656.6 ± 17.18 and 691.6 ± 21.70, and $BRET_{50}$ values (mean ± S.E.M.) were 29.15 ± 2.271 and 29.59 ± 2.804, for untreated and treated cells, respectively.

3.4. In silico structural model of ECL-2 binding to the human serotonin 5-HT_{2A} receptor before and after DTT treatment

In order to analyze how DTT treatment may affect the structural integrity of the serotonin 5-HT_{2A} receptor binding site, we performed a structural analysis of the changes in conformational freedom of ECL-2 before and after DTT treatment. To do so, we started from a model of the serotonin 5-HT_{2A} receptor (see Methods). Using this structure, the ECL-2 region of two different receptor systems was subjected to a Low Mode Analysis with MOE software. In the first, the cysteine bond between ECL-2 and helix 3 was preserved (as found in untreated receptors). In the second, the bond was broken, thus mimicking the effects of DTT. As we can see in the top view of both receptor conditions in **Figure 8**, these result in different populations of ECL-2 conformations. In **Figure 8A**, we see how in the untreated receptor (with an integer cysteine bond, in yellow vdW representation) ECL-2 is more constrained to the extracellular region. This ECL-2 constraint seems to be important for maintaining an open binding pocket that can accommodate an orthosteric ligand (e.g. LSD, orange VdW, see **Fig. 8C**). Conversely, in the receptor with a broken cysteine bond (yellow vdW representation, **Fig. 8B**) ECL-2 adopts a wider variety of conformations. Some of these

conformations protrude deeper into the receptor orthosteric binding pocket leading to collapse of the pocket. A shrunken binding pocket would be incapable of accommodating LSD (orange VdW, **Fig. 8D**) due to a large degree of overlap of ECL-2 with the orthosteric ligand. These observations are consistent with the lower availability of LSD binding sites observed in our experiments.

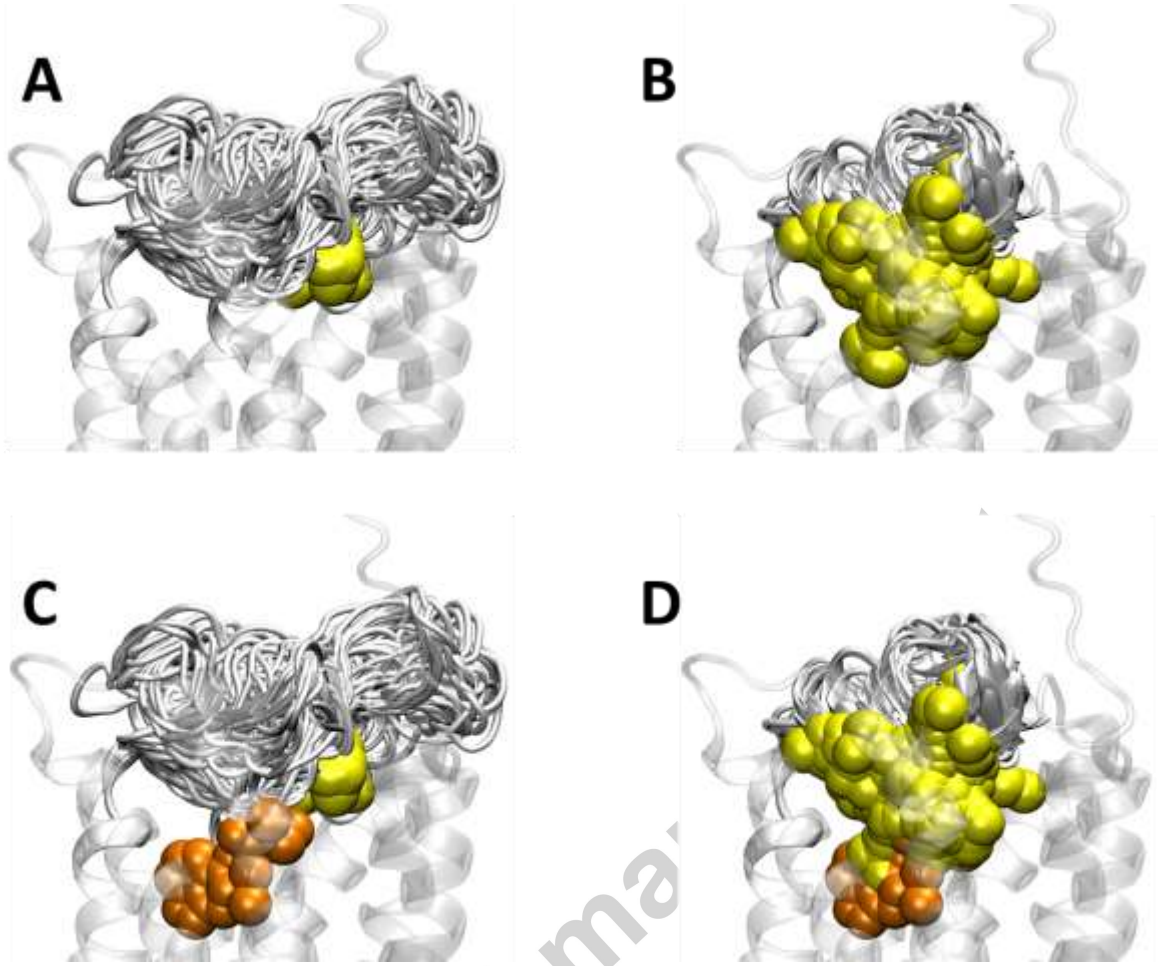

Fig. 8. Conformational analysis of ECL-2. ECL conformational freedom was assessed before (A) and after (B) cysteine bond cleavage. In both representations we can see different conformational states of each receptor condition. The two cysteine residues originally forming the bond are shown in yellow. In order to assess how this different conformational freedom may affect LSD binding, the binding mode of the ligand was assessed. The superimposed structure of LSD to the receptor before (C) and after (D) cysteine cleavage is represented in orange.

4. Discussion

The major finding of this study was that rupture of the disulfide bridge in the serotonin 5-HT_{2A} receptor with the reducing agent DTT alters its binding and activation properties by disturbing its conformation without changing its homodimeric structure.

Ligand binding and the function of the serotonin 5-HT_{2A} receptor after treatment with the reducing agent DTT was analyzed. We used [^{3}H]LSD, a hallucinogenic agonist, in radioligand assays in order to stabilize the active conformations at serotonin 5-HT_{2A} receptors. DTT treatment induced a statistically significant decrease in B_{max} values and in the percentage of specific binding in saturation and association experiments with [^{3}H]LSD, but without affecting radioligand affinity (K_d).

The observed decrease in LSD residence time on DTT-treated cells is consistent with the previously described mutation in ECL-2 (L229A) in serotonin 5-HT_{2A} receptor, because the flexibility of the lid increases (Wacker et al., 2017). Furthermore, DTT treatment induced a significant decrease in the percentage of specific binding without any change in clozapine K_i values in competition assays (11.34 ± 0.71 nM for control and 19.11 ± 2.76 nM for DTT treatment). These results suggest that DTT treatment disrupts disulfide bridges, thereby reducing the number of available [^{3}H]LSD binding sites (lower B_{max}) without modifying the affinity of ligands. Numerous experiments have shown that treatment with DTT causes a decrease in the ligand binding on β-adrenergic receptors (Dohlman et al., 1990; Noda et al., 1994; Vauquelin et al., 1979), dopamine D_2 receptors (Reader et al., 1992), serotonin 5-HT_{1A} receptors (Harikumar et al., 2000) and prostacyclin receptors (Stitham et al., 2006), among others. However, an increase in ligand binding or activation has also been observed in other receptors. Some examples are the histamine H_1 receptor (Carman-Krzan et al., 1984; Dickenson and Hill, 1994; Donaldson and Hill, 1986a, 1986b, 1986c), β-adrenergic receptors (Pedersen and Ross, 1985) and N-methyl-D-aspartate (NMDA) receptors (Reynolds et al.,

1990; Talukder et al., 2011). According to the *in silico* study, the reduced number of binding sites may be the result of the collapse of the binding pocket caused by destruction of the disulfide bridge.

Similar effects on receptor pharmacology have been observed for the β_1-adrenergic receptor (Vauquelin et al., 1979). However, other studies showed that DTT treatment induced a decrease in B_{max} and changes in K_d values (Dorn, 1990; Huang and Rorstad, 1989; Noda et al., 1994; Reader et al., 1992; Wright and Drummond, 1983). Both studies explained the results obtained based on the reduction of a disulfide bridge in the receptor that is important for ligand binding, either by direct participation in ligand recognition or its proximity to binding site.

In a further step, we studied DTT-induced modulation of receptor signalling. We first evaluated the effect of DTT treatment in 5-HT-mediated PLC pathway activation by determining concentration-response curves in the absence and presence of 20 mM DTT. The results showed a statistically significant decrease in E_{max} of IP accumulation in the presence of DTT, although the potency values were unchanged.

Given that clozapine shows functional selectivity with a combination of biphasic and monophasic inhibition curves in both binding and functional assays (Brea et al., 2009), we constructed concentration-response curves for clozapine in the absence and presence of different concentrations of DTT. The results showed a statistically significant decrease in 5-HT E_{max} in both pathways, although the clozapine inhibition profiles observed in treated cells were the same relative to the control. The curves were the same in both untreated and DTT-treated receptors (monophasic in the PLC pathway and biphasic in the PLA_2 pathway) and potency values were unchanged.

Similar results were found in rat forebrain synaptoneurosomes, in which DTT also produced dose-dependent inhibition of IP accumulation produced by glutamate and potassium in the

metabotropic glutamate receptor (Vignes et al., 1992). In the prostacyclin receptor, a decrease in cAMP production was also observed when β-mercaptoethanol (β-ME) was used as the reducing agent, with no effect on the EC_{50} value. In the same study, competition experiments carried out in the presence of β-ME or DTT showed a decrease in [^{3}H]iloprost specific binding without any change in affinity (Stitham et al., 2006).

According to the results of our functional experiments, the dimeric structure of serotonin 5-HT_{2A} receptors was conserved after DTT treatment. However, western-blot experiments have shown that DTT treatment also causes the rupture of GPCR dimers on different receptors (Berthouze et al., 2007; Fay and Farrens, 2013; Michineau et al., 2006; Romano et al., 1996; Zeng et al., 1999; Zeng and Wess, 2000). In order to clarify this question, BRET experiments were carried out to confirm the preservation of the dimeric structure of these receptors. As expected, DTT treatment did not modify the BRET signal, suggesting that breakage of disulfide bridges did not disrupt the dimer. Nevertheless, the binding and functional results suggest that, after DTT treatment, the TM3-ECL-2 disulfide bridge is disrupted, thus allowing the receptor to adopt different conformations. This is consistent with results reported by Lin and colleagues (Lin et al., 1996), who showed that the secondary structure of the β_2-adrenergic receptor had not been disturbed after DTT treatment, but it induced a reversible conformational change in the tertiary structure of the receptor.

We have discarded that DTT may be disrupting cysteine bridges in the intracellular side that could condition the second messenger coupling because DTT is a reducing agent exerting its action in solvent accessible domains, disrupting therefore only extracellular disulfide bridges. Extracellular loops are known to play important functional roles in ligand binding and receptor activation (Avlani et al., 2007; Barington et al., 2016; Conner et al., 2007; Kclo et al., 2005; Nguyen et al., 2016a, 2016b, Palczewski et al., 2000; Peeters et al., 2011; Ragnarsson et al., 2015; Scarselli et al., 2007; Wheatley et al., 2012, 2007). Recently reported crystal

structures show that the conserved disulfide bridge forces ECL-2 to form a lid over the binding pocket, and that ECL-2 contains well defined but rather different secondary structures within the different receptor families (Palczewski et al., 2000; Rasmussen et al., 2007; Shi and Javitch, 2004; Shimamura et al., 2011;Warne et al., 2008). It has also been speculated that the ECL-2 adopts different conformations during ligand binding and receptor activation, first allowing the ligand to enter the binding pocket (open conformation) and secondly stabilizing ligand-stabilized receptor conformations (closed over the ligand). The ECL-2 thus functions as a gatekeeper for entry into the orthosteric binding site. Moreover, ECL-2 is also known to be associated with ligand selectivity by adopting distinct conformations on empty receptor or bound ligand and interacting differently between agonists (total or partial), inverse agonists or antagonists (Banères et al., 2005; de Zwart et al., 1999; Unal et al., 2010). The correct orientation of the ECL-2 is thus restrained by the conserved disulfide bond and plays an important role in producing different functional states of the receptor.

Furthermore, in serotonin 5-HT_{2A} and 5-HT_{2B} receptors a decrease in E_{max} was observed in the β-arrestin pathway when L229A and L209A were mutated respectively, but not in PLC pathway (Wacker et al., 2017). Our results complement the findings of the aforementioned study by showing that the disulfide bridge is disrupted without modifying the primary structure of serotonin 5-HT_{2A} receptor. A decrease in E_{max} was thus also obtained in PLA_2 and PLC pathways, suggesting a role for the disulfide bridge in ligand binding and activation.

In summary, our results show that the disulfide bridge between TM3 and ECL-2 is essential for serotonin 5-HT_{2A} receptor signalling in both PLA_2 and PLC pathways, but not for the homodimeric nature of these receptors. This reveals the integrity of the ECL-2 epitope, which should be explored for developing novel ligands acting as allosteric modulators of serotonin 5-HT_{2A} receptors.

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Conflict of interest

The authors declare no conflicts of interest.

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