

**ORIGINAL ARTICLE**

Adenosine A_{2A} receptor blockade reverts hippocampal stress-induced deficits and restores corticosterone circadian oscillation

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Maternal separation (MS) is an early life stress model that induces permanent changes in the central nervous system, impairing hippocampal long-term potentiation (LTP) and spatial working memory. There are compelling evidences for a role of hippocampal adenosine A_{2A} receptors in stress-induced modifications related to cognition, thus opening a potential window for therapeutic intervention. Here, we submitted rats to MS and evaluated the long-lasting molecular, electrophysiological and behavioral impairments in adulthood. We then assessed the therapeutic potential of KW6002, a blocker of A_{2A} receptors, in stress-impaired animals. We report that the blockade of A_{2A} receptors was efficient in reverting the behavior, electrophysiological and morphological impairments induced by MS. In addition, this effect is associated with restoration of the hypothalamic-pituitary-adrenal axis (HPA-axis) activity, as both the plasma corticosterone levels and hippocampal glucocorticoid receptor expression pattern returned to physiological-like status after the treatment. These results reveal the involvement of A_{2A} receptors in the stress-associated impairments and directly in the stress response system by showing that the dysfunction of the HPA-axis as well as the long-lasting synaptic and behavioral effects of MS can be reverted by targeting adenosine A_{2A} receptors. These findings provide a novel evidence for the use of adenosine A_{2A} receptor antagonists as potential therapy against psychopathologies.

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Keywords: adenosine A_{2A} receptors; corticosterone; hippocampus; HPA-axis; maternal separation; stress

Introduction

Exposure to stress has deleterious effects on brain structure and function, which could be manifested either immediately after stress,¹ as a long-term vulnerability to cognitive deficits² or even as an increased susceptibility to neuropsychiatric disorders, where stress has a major role.^{3,4}

Mother–infant interaction is a key factor for brain maturation and disease susceptibility which in humans can manifest in cognitive and behavioral disorders later in life.^{5,6} In rats, the daily separation of the litter from their mothers for 180 min each day during postnatal days (PNDs) 2–14 will result in an alteration of maternal behavior, namely with a

significant reduction in licking/grooming duration.⁷ During this period, the hippocampus, which is critically involved in long-term memory formation⁸ and is also a primary target for stress hormones in the central nervous system,^{1,9} goes through great development. The majority of hippocampal granule neurons develop and extend their axons between PND 1 and 21¹⁰ and the peak period of neurogenesis and mossy fiber outgrowth overlaps with the stress hyporesponsive period (PND 4–14) in neonatal rats.¹¹ This will induce changes that persist throughout adult life at the level of gene expression, neurochemistry, electrophysiology properties and morphology^{12,13} with behavioral and neuroendocrine signs of cognitive deficits and over-activation of the hypothalamic-pituitary-adrenal axis (HPA-axis) as adults.^{7,14–16}

Adenosine receptors in the hippocampus are important modulators of synaptic transmission and neuronal excitability. Glutamatergic synaptic transmission in physiological conditions is controlled

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negatively by the dominant adenosine A₁ receptors, and positively to a lesser extent by A_{2A} receptors.¹⁷ Interestingly, this pattern appears to be modified in the aged hippocampus, with a marked increase in the expression of A_{2A} receptors and a decrease in the expression of A₁ receptors.^{18,19} These changes are accompanied by a strong direct facilitatory effect of A_{2A} receptors on the release of glutamate.²⁰ This is also observed in other situations associated to neuronal dysfunction, such as epilepsy, acute stress or animal models of Alzheimer's disease,²¹ which suggests a deleterious contribution of A_{2A} receptors to these conditions. The blockade of A_{2A} receptors was proven beneficial against synaptic loss associated with acute stress in the hippocampus.²² Interestingly, cognitive impairments also occur when excessive levels of corticosteroids are attained due to disease, or due to hypersecretion in response to a stressor.^{23,24}

However, it is still unknown the extent to which A_{2A} receptors are involved in the long-term effects of early life stress. Here, we submitted rats to maternal separation (MS) and evaluated the long-lasting molecular, electrophysiological and behavioral impairments at adult age. We then assessed the therapeutic potential of blocking endogenous activation of A_{2A} receptors, by administering a selective antagonist, KW6002 (istradefylline), orally for 1 month to stress-impaired animals. We report that the blockade of A_{2A} receptors was efficient in reverting the long-lasting behavior, morphological and electrophysiological impairments induced by MS. We also show that this effect is associated with the re-establishment of the HPA-axis activity, as both the plasma corticosterone levels and hippocampal glucocorticoid receptor expression pattern returned to physiological-like status after the treatment.

Materials and methods

Animals

Pregnant Wistar rats were purchased (Harlan, Barcelona, Spain) in mid-gestation and were due in our animal facility. All animals were handled according to European Community guidelines and Portuguese law on animal care (1005/92). The animals that were killed by decapitation were anesthetized under halothane atmosphere.

MS protocol

The protocol used has been previously validated and described.²⁵ Wistar dams and their litters were assigned either to the control (CTR—non-separated) or to the MS groups as described before.²⁶ To exclude artifacts from genetic background, at PND 2, all the litters were collected together, gender assessed and the pups were randomly distributed to foster dams (gender proportion maintained). MS pups were removed from their cages as a group from PND 2 to 14, for 180 min, daily, at 9 am, and placed in an isolation cage in an adjacent room kept at 32.0 ± 0.5 °C. At the end of the separation period,

pups were returned to their home-cage and rolled in the soiled home cage bedding before reuniting with the mother. CTR pups were not handled and were maintained in their home-cages until weaning. At day 21 the pup's gender was confirmed, males weaned and housed in groups of 5–8 animals per cage until use at adult age (8–14 weeks; according to diagram in Supplementary Figure S1).

Oral administration of the drug

KW6002 (istradefylline), a selective adenosine A_{2A} receptor antagonist²⁷ was orally administered diluted in the drinking water, being continuously available. The weight of the animals and the volume intake were assessed twice a week and the concentration of the solution was adjusted so that the drug intake was maintained at 3 mg kg⁻¹ per day. Animals were divided in four groups: CTR or MS, drinking vehicle (0.025% methylcellulose) and CTR KW or MS KW drinking KW6002 (3 mg kg⁻¹ per day, 0.025% methylcellulose). The treatment started at 4–6 weeks old, and was prolonged for 1 month until sacrifice. The KW6002 administration was kept throughout the behavioral assessments.

Corticosterone quantification

Blood was extracted from the tail, in animals previously handled to minimize stress and without anesthesia, at two different time points, 8 am (nadir) and 8 pm (zenith). The plasma was isolated by centrifugation at 2000 g, 4 °C for 15 min and corticosterone quantified by radioimmunoassay using the rat corticosterone ³H kit from MP Biomedicals, UK according to the manufacturer's protocol.

Behavioral assessments

CTR, MS, CTR KW, MS KW were first handled for 5 days before testing the behavior assays, that were performed in the following sequence: open-field (OF), Elevated plus maze (EPM) and Morris water maze (MWM).²⁸ Rats were given spatial acquisition training consisting of four trials/day for 4 consecutive days, as performed before.²⁹ On the 5th day a probe test was given in which the platform was removed and animals were allowed to swim freely for 60 s while recording the percentage of time spent on each quadrant. The latency to found the platform during acquisition and the percentage of time in the platform quadrant in probe test were used to evaluate hippocampal-dependent memory. EPM: The maze is shaped like a plus sign and consists of two 'open' and two 'closed' arms, arranged perpendicularly, and elevated 50 cm above the floor. Each animal was placed at the center of the equipment, facing an open arm. Each test lasted 5 min and all testing sessions were performed between 10:00 am and 17:00 pm in a sound-attenuated room. The maze was cleaned with a 70% ethanol solution between each animal. The total time spent in the open arms and the total arms entries (number of entries in open + closed arms) were used as anxiety and locomotor measures.³⁰ Open field:

The animals were placed at the center of the arena (66 × 66 cm) and allowed to explore for 5 min. Changes in mean speed and path length of the subjects were continuously monitored by an automated tracking system (Smart 2.5, PanLab, Barcelona, Spain). The maze was cleaned with a 70% ethanol solution between each animal.

Histological procedures

The day after the last testing session, five rats from each experimental group were perfused transcardially with phosphate-buffered saline, under deep pentobarbital anesthesia. Brains were removed and split into two hemispheres, and processed either for stereology, or for Golgi-Cox staining according to the procedures previously described.^{31,32} Briefly, for stereology the left hemispheres were included in glycolmethacrylate (Tecnovit 7100; Heraeus Kulzer, Werheim, Germany) and every other microtome-cut section (30 μm) was then collected on a gelatinized slide, stained with Giemsa, and mounted with Entellan New (Merck, Darmstadt, Germany). The shrinkage factor was calculated according to Madeira *et al.*³³ For 3D neuronal reconstructions, hemispheres were removed and immersed in Golgi-Cox solution (a 1:1 solution of 5% potassium dichromate and 5% mercuric chloride diluted 4:10 with 5% potassium chromate³⁴) for 14 days; hemispheres were then transferred to a 30% sucrose solution (3 days), before being cut on a vibratome. Coronal sections (200 μm thick) were collected in 6% sucrose and blotted dry onto gelatin-coated microscope slides. They were subsequently alkalized in 18.7% ammonia, developed in Dektol (Kodak, Linda-a-Velha, Portugal), fixed in Kodak Rapid Fix (prepared as manufacturer instructions), dehydrated through a graded series of ethanols, and cleared in xylene before being mounted and coverslipped. Slides were coded before morphometric analysis in both sets.

Region and layer boundaries

We analyzed the following regions of the hippocampal formation: the dentate gyrus (including polymorphic, granule cell layer and molecular layer), CA1 (strata oriens, pyramidale, radiatum and lacunosum-moleculare) and CA3 (strata oriens, pyramidale, lucidum and radiatum). The above-mentioned regions were outlined according to the atlas of Paxinos and Watson,³⁵ based on noticeable cytoarchitectural differences.³⁶

Stereological procedures

Volume estimations were performed using StereoInvestigator software (MicroBrightField, Williston, VT, USA) and a camera (DXC390; Sony, Tokyo, Japan) attached to a motorized microscope (Axioplan 2; Zeiss, Oberkochen, Germany). Cavalieri's principle³⁷ was used to assess the volume of each region. Briefly, every 10th section was used and its cross-sectional area was estimated by point counting at a final magnification of × 112. For this, we randomly super-

imposed onto each area a test point grid in which the interpoint distance, at tissue level, was as follows: (1) 150 μm for the three layers of the dentate gyrus, (2) 250 μm for the three layers of CA1 and CA3. The volume of the region of interest was calculated from the number of points that fell within its boundaries and the distance between the systematically sampled sections.

Dendritic tree analysis

Three-D reconstructions of representative Golgi-impregnated neurons from CA1 were made. The criteria used to select neurons for reconstruction were as follows: (i) full impregnation of the neurons along the entire length of the dendritic tree; (ii) dendrites without significant truncation of branches; (iii) relative isolation from neighboring impregnated neurons to avoid interference with the analysis; (iv) no morphological changes attributable to incomplete dendritic impregnation of Golgi-Cox stain. Golgi-impregnated pyramidal-like neurons of the CA1 region were readily identified by their characteristic pyramidal or piriform soma, spine-sparse primary dendrites and spine-dense secondary dendrites (Figure 2e for representative reconstructions). For each selected neuron, all branches of the dendritic tree and the location of all dendritic spines were reconstructed at × 600 magnification, using a motorized microscope (Carl Zeiss Axioplan 2, Hamburg, Germany, with oil-objectives), attached to a camera (DXC-390, Sony, Tokyo, Japan) and NeuroLucida software (MicroBrightField). Three-D analysis of the reconstructed neurons was performed using NeuroExplorer software (MicroBrightField). In each hemisphere, 10 CA1 pyramidal neurons were reconstructed; as a result in this study we have analyzed 200 neurons. Several aspects of dendritic morphology were examined. To assess overall changes, total dendritic length, number of ramifications and number of dendrites were compared between groups. Sholl analysis was performed to assess changes in the ramification pattern.

Electrophysiological recordings

After decapitation the brain was rapidly removed and the hippocampi were dissected free in ice-cold Krebs solution composed of (mM): NaCl 124; KCl 3; NaH₂PO₄ 1.25; NaHCO₃ 26; MgSO₄ 1; CaCl₂ 2; and glucose 10, previously gassed with 95% O₂ and 5% CO₂, pH 7.4. 400 μm slices were obtained with a McEwen tissue shopper and field excitatory postsynaptic potentials (fEPSPs) were recorded as previously²⁹ in *stratum radiatum* of the CA1 area. Input-output (I/O) curves and long-term potentiation (LTP, 100 Hz, 1 s, 100 pulses induced at 0.5 mV/ms; < 50% max) were recorded as previously. The second hippocampus was rapidly frozen in liquid nitrogen for further analysis.

Tissue processing

Samples were homogenized either in radio immunoprecipitation-assay buffer (50 mM Tris, 1 mM EDTA,

150 mM NaCl, 0.1% SDS, 1% NP 40, pH 8;³⁸ or in 0.32 M sucrose solution with 50 mM Tris at pH 7.6¹⁹ supplemented with protease inhibitors (ROCHE, Mannheim, Germany). The first were centrifuged at 14 000 g for 15 min, and the second at 1000 g for 10 min, at 4 °C. The supernatant was collected, corresponding to whole-tissue lysate and whole-tissue homogenate, respectively. For membrane isolation the whole-tissue homogenate was centrifuged at 14 000 g for 12 min, at 4 °C, the pellet is the membrane fraction. Protein was quantified using the BioRad Protein or DC Protein based on procedures previously described.^{39,40}

Saturation-binding assays

The radioligand-binding experiments were performed as described⁴¹ with membrane fractions. Briefly, [³H]ZM 241385 binding (0–10 nM) was for 1 h with 20–35 µg of protein/well for striatum membranes and [³H]DPCPX (0–10 nM) binding was for 2 h with 40–60 µg protein/well of hippocampal, 60–100 µg protein/well of cortex and 20–40 µg protein/well of striatum membranes. Specific binding was determined subtracting the non-specific binding, measured in the presence of 2 µM of XAC and normalized for protein concentration. Radioactivity was determined after 12 h with an efficiency of 55–60% for 2 min. All binding assays were performed in triplicate.

Immunoblotting

Lysates or homogenates were denatured with 5 × sample buffer (350 mM Tris pH 6.8, 30% glycerol, 10% SDS, 600 mM DTT and 0.012% Bromophenol blue, pH 6.8) and heated either at 95 °C for 5 min or at 60–70 °C for 30 min, respectively, and further processed as before.²⁹ A_{2A}R and GABA_AR antibodies (Upstate/Millipore, Temecula, CA, USA; 05–717 and 05–474) were at 1:2000, GR, MR (Santa Cruz Biotechnology, Heidelberg, Germany; sc-1004 and sc-11412) at 1:1000 and 1:200, NMDAR2B (Cell Signaling, Danvers, MA, USA; D15B3) at 1:1000 and glutamate receptor one (GluR1) (Millipore, 05–855) at 1:6000. Optical density was determined with Image-J software and normalized to the respective β-actin or α-tubulin band density.

Drugs

A_{2A}R-selective antagonist, 2-(2-Furanyl)-7-(2-phenylethyl)-7H-pyrazolo(4,3-e)(1,2,4)triazolo(1,5-c)pyrimidin-5-amine (SCH58261) and the non-selective adenosine receptor antagonist 8-(4-((2-minoethyl)amino)carbonylmethoxyphenyl)xanthine (XAC) were purchased from Tocris Cookson, UK. These solutions were diluted in the assay solution from 5 mM stock aliquots made in DMSO stored at –20 °C. A_{2A}R-selective antagonist, (*E*)-8-(2-(3,4-dimethoxyphenyl)-vinyl)-1,3-diethyl-7-methyl-3,7-dihydropurine-2,6-dione (KW6002, istradefylline) was synthesized according to a published procedure.⁴² The purity of the product was determined by HPLC analysis coupled to electro-spray ionization mass spectrometry and was > 98%.

Adenosine deaminase (from calf intestine 10 mg/2 ml, EC 3.5.4.4) was from ROCHE; A₁R-selective antagonist, (propyl-³H)8-cyclopentyl-1,3-dipropylxanthine ([³H]DPCPX, specific activity 100 Ci per mmol) was from Amersham, Buckinghamshire UK, and A_{2A}R-selective antagonist, 4-(2-(7-Amino-2-(2-furyl)(1,2,4)-triazolo(2,3-a)(1,3,5)triazin-5-ylamino)ethyl)phenol, ([³H]ZM 241385, specific activity 27.4 Ci per mmol) was from ARC, St Louis, MO, USA. All these drugs were diluted directly in the incubation solution each day. HRP-coupled secondary antibodies were from Santa Cruz Biotechnology. All other reagents used were of the highest purity available either from Merck or Sigma Aldrich, Madrid, Spain.

Statistics

Values presented are mean ± s.e.m. of *n* experiments. To test the significance of the differences between CTR and MS groups, an unpaired Student's *t* test was used. When comparing CTR, MS, CTR KW and MS KW groups a one-way ANOVA was used, followed by a Bonferroni's Multiple Comparison *post hoc* test. For the Sholl analysis of reconstructed neurons a repeated measures analysis was used. For the saturation binding curves an *F*-test was used to determine whether the competition curves were best fitted by one or two independent binding site equation and if the parameters obtained from the CTR and MS saturation curves (*B*_{max} and *K*_D) were different. For the analysis of the MWM acquisition curve and corticosterone circadian oscillation, the statistical differences were evaluated using two-way ANOVA repeated measures test. Values of *P* < 0.05 were considered to be statistically significant.

Results

MS induces long-lasting regional effects in the brain
MS induces numerous changes in the brain particularly in the hippocampus.^{43,44} The balance between mineralocorticoid and glucocorticoid receptors (MR and GR, respectively) can determine the impact of stress in different brain areas.⁴⁵ We quantified the levels of GR and MR in the hippocampus, cortex and striatum of adult animals previously subjected to MS (Figure 1a). MS has led to a long-lasting decrease of the GR levels that was more evident in the hippocampus (0.74 ± 0.04 of CTR, *n* = 8, *P* < 0.05) than in cortex (0.86 ± 0.03 of CTR, *n* = 4, *P* < 0.05) or striatum (0.90 ± 0.03 of CTR, *n* = 4; *P* < 0.05). MR levels were not modified in any of the brain areas analyzed (Figure 1b). Concomitant changes on the levels of adenosine receptors were observed. Comparing with CTR, MS animals presented a 1.49 ± 0.04-fold increase (*n* = 9; *P* < 0.05) in the levels of A_{2A}R that was restricted to the hippocampus (Figure 1c). A hippocampal-specific decrease in the A₁R levels was also observed; *B*_{max} values were of 1202 ± 33 fmol per mg protein (*n* = 4) for CTR animals and 1073 ± 23 fmol per mg protein for MS animals, (*n* = 4; *P* < 0.05; Figure 1d).

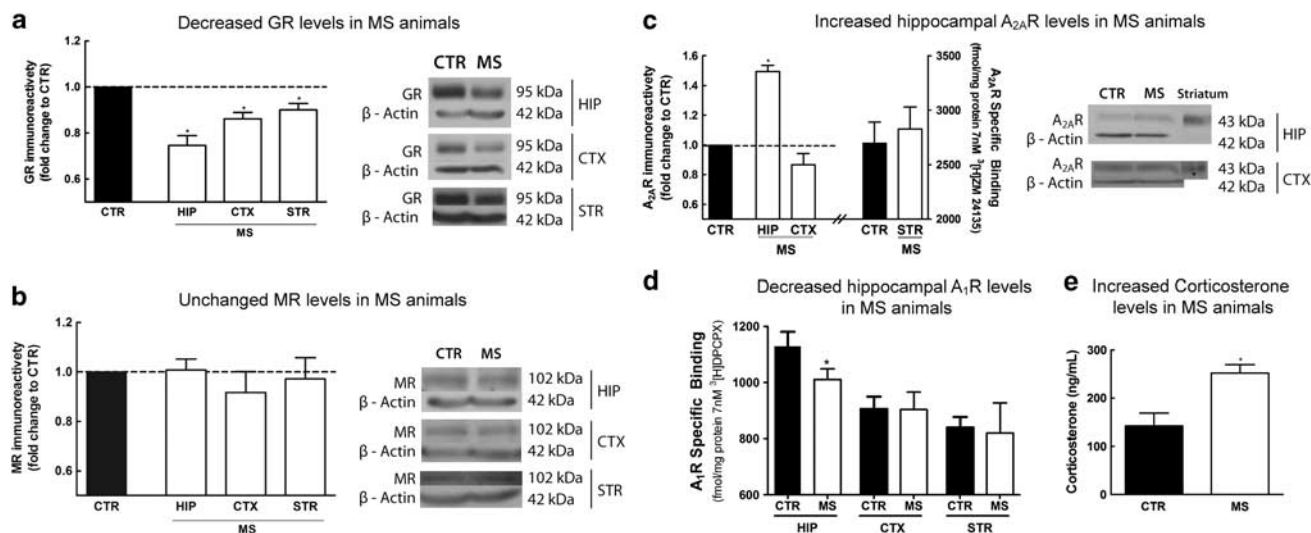


Figure 1 Region-specific effects of MS. MS induced region-specific changes in, GR (a) MR (b) A_{2A}R (c) and A₁R (d) and an increase in plasmatic corticosterone levels (e). Protein levels of GR, MR (in all brain areas) and A_{2A}R (in hippocampus and cortex) were evaluated by western blotting. Specific immunoreactivity was normalized to that of β -Actin or α -tubulin. For A_{2A}R immunoreactivity 5 μ g of striatum were used as positive control. Results are the mean \pm s.e.m. of 3–9 experiments; * P <0.05, comparing with CTR, calculated using an unpaired Student *t*-test. A₁R levels in all areas and A_{2A}R levels in striatum were measured by saturation-binding curves with the A₁ or A_{2A} receptor selective antagonist [³H]DPCPX or [³H]ZM 24135, respectively. [³H]DPCPX or [³H]ZM 24135 (7 nM) were incubated with 20–100 μ g of membranes in a final volume of 300 μ l for 2 h/1 h at room temperature. The ordinates represent the specific binding obtained upon subtraction of the non-specific binding, determined in the presence of 2 μ M of XAC, from total binding. Values are the mean \pm s.e.m. of 4–5 experiments performed in triplicate. * P <0.05 calculated using an *F*-test compared with CTR. Corticosterone levels in the morning period (8 am) were measured by radioimmunoassay using the rat corticosterone [³H] kit. Results are mean \pm s.e.m. of nine experiments; * P <0.05 obtained using an unpaired Student *t*-test.

MS animals also presented a sustained increase in plasmatic corticosterone levels (Figure 1e).

Adenosine A_{2A} receptors are involved in synaptic changes induced by MS

To evaluate the impact of stress in synaptic transmission and plasticity, fEPSPs were measured in the CA1 area of the dorsal hippocampus. Basal synaptic transmission was accessed by performing I/O curves, whereas synaptic plasticity was evaluated by LTP induced by high frequency stimulation (100 Hz, 1 s).

The I/O curve was not modified by MS (Figure 2a, $n=3$). However, LTP magnitude (Figure 2b) was reduced in MS animals to $34.4 \pm 2.7\%$ from $50.7 \pm 3.4\%$ of potentiation obtained in CTR ($n=7$, P <0.05).

To evaluate whether the increase in A_{2A} adenosine receptors was involved in the impairments observed in synaptic plasticity, LTP was induced in the presence of SCH58261 (50 nM), a selective A_{2A}R antagonist. The *ex vivo* blockade of A_{2A}R reverted the LTP deficits induced by MS without affecting LTP magnitude in CTR animals ($53.1 \pm 3.7\%$ and $57.3 \pm 1.7\%$ of potentiation, respectively, $n=4-7$, P >0.05; Figure 2c).

Moreover, the *in vivo* administration of the A_{2A}-selective antagonist KW6002 for 1 month to adult MS animals was also able to revert the LTP deficits observed ($47.6 \pm 3.9\%$ of potentiation in MS KW animals, $n=4$, P >0.05 versus CTR; Figure 2d).

In order to better characterize the plastic changes observed in the electrophysiological studies, a 3D morphological analysis of dendritic arborizations of CA1 pyramidal neurons was performed. Data revealed a significant treatment effect in the total length of apical dendrites of pyramidal neurons ($F=7.371$, P <0.001), and in the total number of apical dendrite ramifications ($F=9.272$, P <0.001); *post-hoc* analysis showed that MS induced a significant decrease in the total length of apical dendrites when compared with CTR (P <0.05) (Figure 2e). Similarly, MS pyramidal neurons had significantly less ramifications in apical dendrites when compared with CTR (P <0.05). Both parameters were restored by KW6002 treatment (P >0.05 versus CTR). There were no significant differences in the structure or number of basal dendrites. Sholl analysis showed coherent changes in the pattern of ramification ($F=5.691$, P <0.001). The changes in apical dendrite arborizations observed in MS animals when compared with CTR (P <0.05) were reverted by KW6002 (Supplementary Figure S2).

To further evaluate the consequences to the overall morphology we undertook an estimation of hippocampal formation volumes. Our data revealed that neither MS nor KW6002 treatment significantly affected volumetric estimates (Supplementary Table S1).

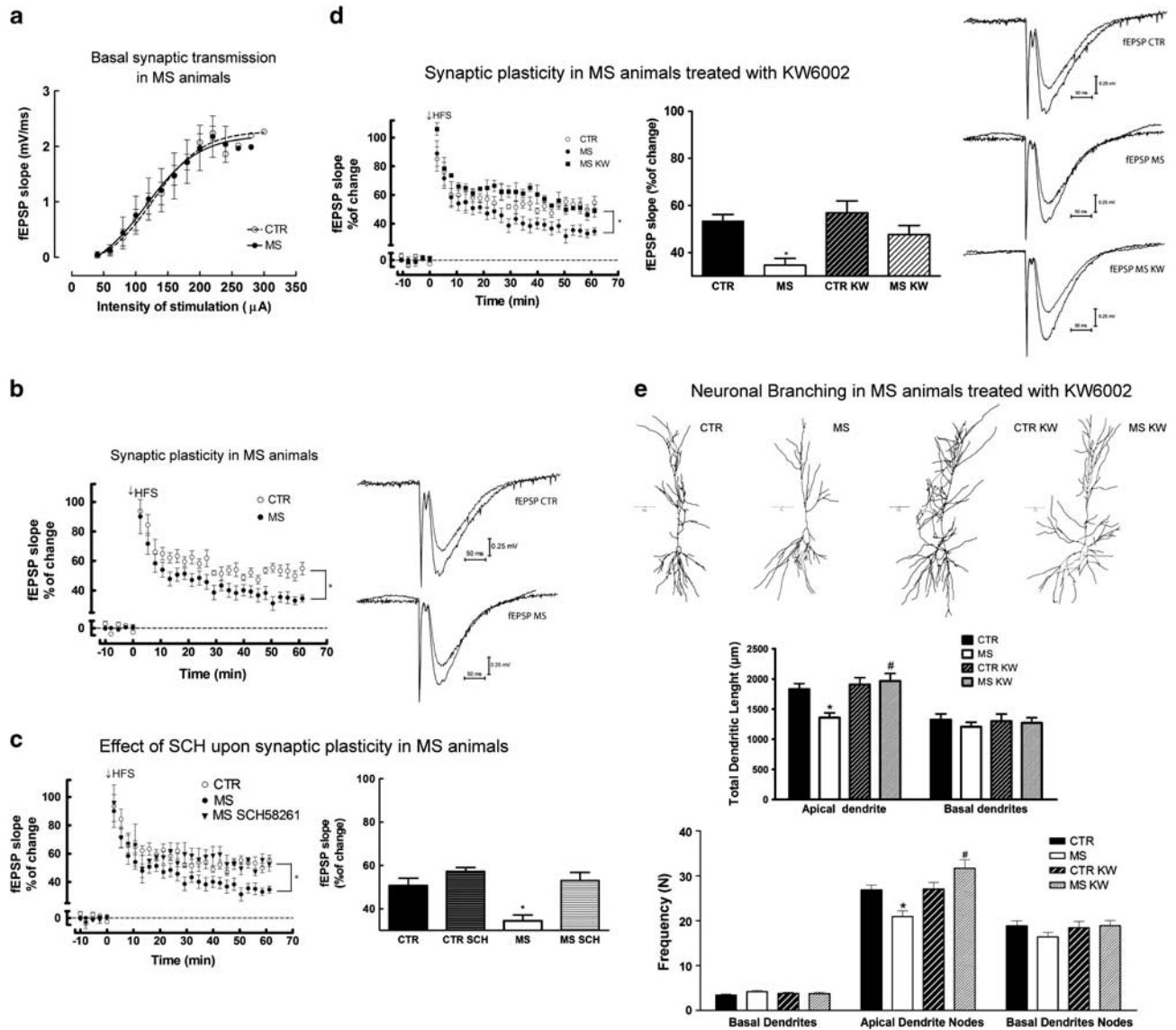


Figure 2 Involvement of adenosine A_{2A} receptors in the synaptic changes induced by MS. **(a)** I/O curves performed to evaluate synaptic transmission in CTR and MS animals and **(b)** LTP (high frequency stimulation, 100 Hz, 1 s), used to evaluate synaptic plasticity. Representative recordings of the fEPSPs obtained both for CTR and MS animals before LTP induction and in the last 10 min are presented. The effect of SCH58261 (50 nM) application for 30 min before LTP induction and throughout the protocol is shown in **(c)**. The outcome of KW6002 treatment upon LTP is in **(d)** with representative recordings of the fEPSPs obtained for CTR, MS and MS + KW6002 animals, before LTP induction and 1 h after LTP. Bar graphs are obtained by making the average of the last five timepoints of each experiment. Results are the mean \pm s.e.m. of 3 **(a)** or 4–7 experiments * P < 0.05, comparing with CTR. **(e)** Administration of KW6002 reverses dendritic atrophy induced by MS in CA1 pyramidal neurons. Upper panel depicts representative schematics of 3D reconstructions of CTR, MS, CTR KW and MS KW CA1 neurons. * P < 0.05, comparing with MS, calculated using a one-way ANOVA followed by a Bonferroni's Multiple Comparison Test.

Oral administration of a selective A_{2A} receptor antagonist reverts the stress-induced anxious behavior and learning-deficits

We then evaluate the extent to which A_{2A}R are involved in the stress-induced behavior alterations, by the administration of the A_{2A}R-selective antagonist, KW6002, to adult MS animals.

Anxious behavior and hippocampal-dependent memory were evaluated by the EPM and the MWM

paradigms, respectively. In the EPM, MS animals presented a higher anxious-related behavior (spent less time in the open arms, $11.4 \pm 2.0\%$ versus $28.9 \pm 5.3\%$ in CTR, $n = 8–11$, $P < 0.05$), validating the MS stress induction. The hyperanxious behavior in MS animals was reverted upon treatment with KW6002 (time in open arms: $27.3 \pm 4.4\%$, $n = 8$, $P > 0.05$ versus CTR; Figure 3a). KW6002 treatment by itself had no effect in the anxious behavior of CTR

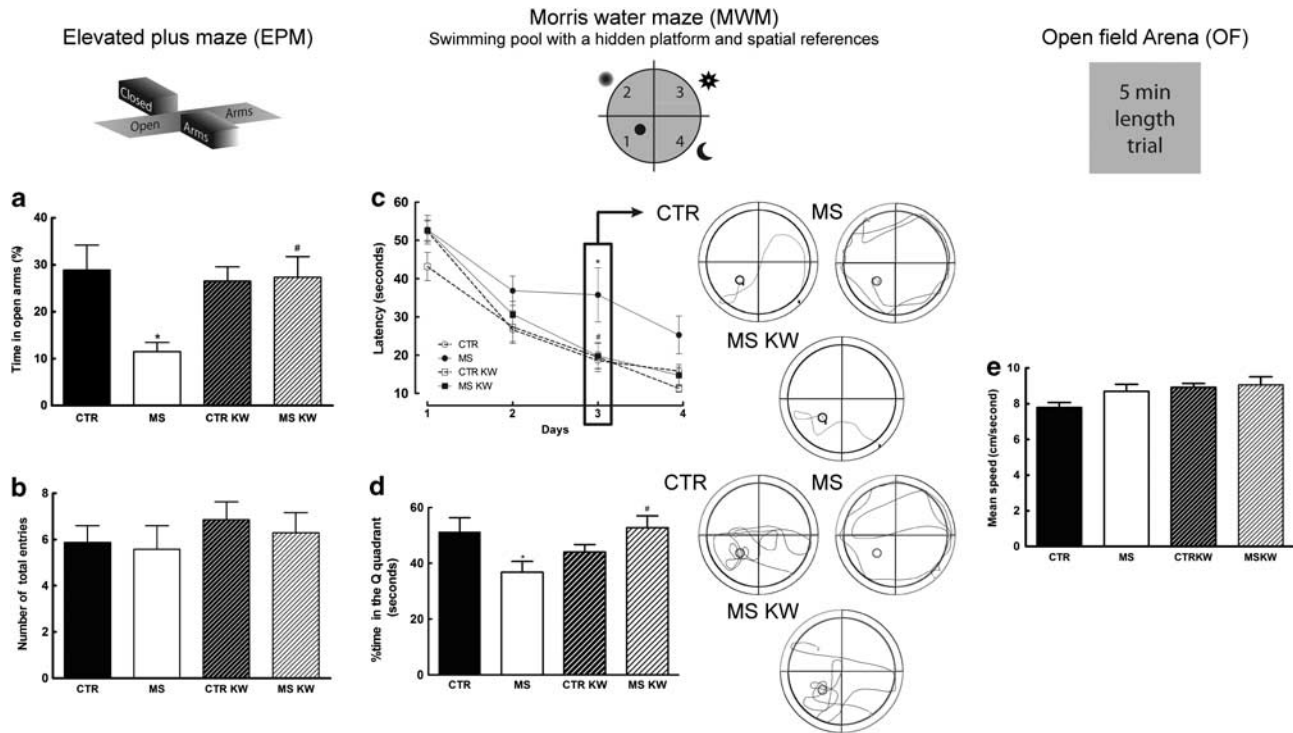


Figure 3 Administration of KW6002 reverts the stress-induced anxious behavior and learning deficits. Anxious behavior (a, b) and locomotor activity (e) were evaluated by the elevated-plus-maze-test and open-field, respectively. Hippocampal-dependent memory performance was assessed by the MWM test, in which acquisition (c) and retention (d) were evaluated. Results are the mean \pm s.e.m. of 6–9 animals; * $P < 0.05$, comparing with CTR, [#] $P < 0.05$ comparing with MS, calculated using two-way ANOVA repeated measures (a) or one-way ANOVA followed by a Bonferroni's Multiple Comparison Test.

animals ($26.5 \pm 3\%$, $n = 7$, $P > 0.05$), neither had an impact in locomotor performance in EPM (Figure 3b). On the MWM, the learning ability (Figure 3c) of MS animals was impaired, so that at day three MS performed worse than CTR animals ($F(3,132) = 8.56$, $n = 6$, $P < 0.0001$). These deficits were reverted by blocking A_{2A}R *in vivo* ($n = 10$, $P < 0.05$). The retention ability of MS animals was also compromised, as in the probe test MS animals spent less time in the platform quadrant than CTR ($36.8 \pm 3.9\%$, $n = 8$; $P < 0.05$ versus $51.3 \pm 5.0\%$, $n = 7$; Figure 3d). When treated with the A_{2A}R antagonist the retention ability of MS animals was restored ($52.8 \pm 4.2\%$ of the time in the platform quadrant; $n = 8$, $P > 0.05$; Figure 3d). KW6002 by itself had no effect in the performance of CTR animals.

A_{2A}R are highly abundant in striatum exerting important effects in motor control.⁴⁶ To evaluate directly locomotor activity, the open-field arena test was used. In accordance with data obtained in the EPM, neither MS nor the KW6002 treatment induced changes in the locomotor performance of the animals, as no alterations were observed in the mean speed on the open-field arena (Figure 3e).

Oral administration of a selective A_{2A} receptor antagonist re-establishes stress-induced modifications on synaptic markers

Given the positive effects of the *in vivo* KW6002 treatment in behavior, in *ex vivo* synaptic plasticity

and in neuronal morphology, we next explored the molecular changes that could underlie the observed therapeutic effects. The levels of A_{2A}R and GR were measured in the hippocampus of CTR and MS animals treated with KW6002. Given the role of AMPA, GABA_A and NMDA receptors in synaptic transmission and plasticity, AMPA-GluR1, GABA_A- $\beta_{2/3}$ and NMDAR2B subunits levels were also evaluated. AMPA-GluR1 levels in MS animals were significantly decreased comparing with CTR (0.81 ± 0.02 , $n = 9$, $P < 0.05$; Figure 4a). These values were re-established by KW6002 (0.98 ± 0.03 , $n = 4$, $P > 0.05$ versus CTR). GABA_A- $\beta_{2/3}$ levels decreased in MS animals (0.78 ± 0.02 , $n = 8$; $P < 0.05$; Figure 4b) and increased to 1.15 ± 0.06 of CTR ($n = 6$, $P < 0.05$) upon KW6002 treatment. The levels of the NMDAR2B subunit were not altered by MS nor by KW6002 treatment ($n = 5$; Figure 4c). Furthermore, the increased levels of A_{2A}R observed in MS animals (1.49 ± 0.04 -fold to CTR, $n = 9$; $P < 0.05$) were maintained in MS KW animals (1.56 ± 0.05 -fold to CTR, $n = 5$, $P > 0.05$; Figure 4d). The KW6002 administration alone increased the levels of A_{2A}R to 1.25 ± 0.09 of CTR ($n = 5$, $P < 0.01$; Figure 4d), as could be expected from a chronic administration of receptor antagonist. The GR levels (Figure 3e) were not changed by KW6002 in CTR animals ($n = 7$, $P > 0.05$); however, when KW6002 was administered to MS animals the levels of GR increased to values similar to CTR (1.033 ± 0.04 , $n = 6$, $P > 0.05$).

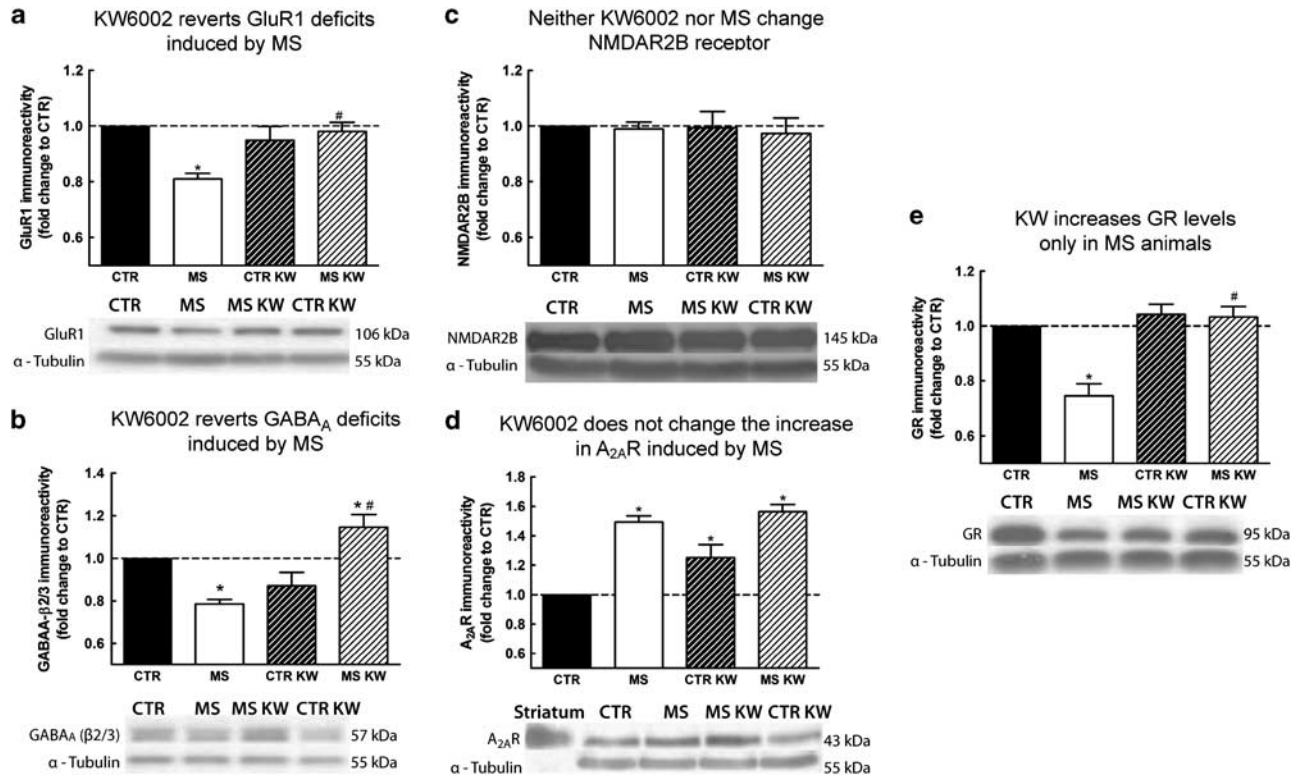


Figure 4 Administration of KW6002 reverts the synaptic changes induced by MS. The effects of the treatment with KW6002 in the levels of GluR1 subunit of AMPA receptors (**a**), β2/3 subunit of GABA_A receptors (**b**), NMDAR2B (**c**), A_{2A}R (**d**), and GR (**e**) were evaluated by western blotting. Specific immunoreactivity normalized to that of α-tubulin. Results are the mean ± s.e.m. of 4–9 experiments; **P* < 0.05, comparing with CTR and #*P* < 0.05, comparing with MS, calculated using a one-way ANOVA followed by a Bonferroni's Multiple Comparison Test.

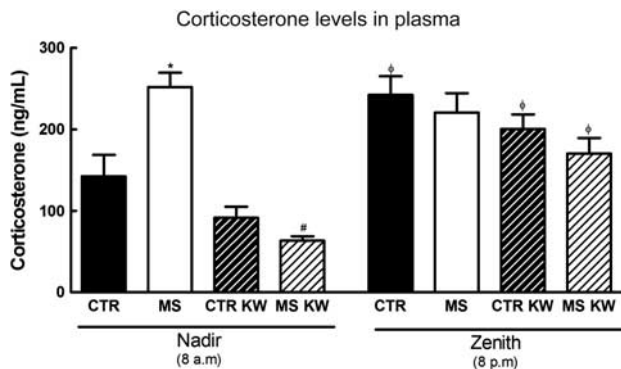


Figure 5 The KW6002 administration re-establishes the corticosterone circadian oscillation. Corticosterone levels in the plasma measured at nadir and zenith. Results are mean of 6–9 animals. **P* < 0.05, comparing with CTR, #*P* < 0.05 comparing with MS, †*P* < 0.05, comparing with am values, calculated using a one-way ANOVA followed by a Bonferroni's Multiple Comparison Test.

The A_{2A}R antagonist re-establishes the corticosterone circadian oscillation

As the blockade of A_{2A}R reestablishes the GR levels in the hippocampus, we hypothesized that this could involve a regulation of the HPA-axis function, which is compromised due to the early life stress.¹⁴ HPA-axis

activity was evaluated by measuring circadian changes in plasmatic corticosterone levels (Figure 5).

CTR animals had the expected circadian oscillation, with corticosterone levels significantly elevated at 8 pm comparing with those measured at 8 am MS animals present significantly higher corticosterone levels already at 8 am ($234 \pm 13 \text{ ng ml}^{-1}$ versus $142 \pm 27 \text{ ng ml}^{-1}$; *P* < 0.05, *n* = 9) comparing with CTR at the same time of the day, and the absence of a circadian oscillation. Animals treated with KW6002 had a restored circadian variation, with plasmatic corticosterone levels at 8 am similar to CTR ($63 \pm 5 \text{ ng ml}^{-1}$), (*F*(3,24) = 9.04, *P* = 0.0003). KW6002 alone did not affect corticosterone levels, neither at zenith nor at nadir.

Discussion

The data now reported reveal that adenosine A_{2A} receptor activation is directly involved in the stress deleterious effects in the brain. We show, for the first time, that the administration of a selective adenosine A_{2A} receptor antagonist reverts the long-lasting consequences of stress on spatial memory, synaptic plasticity and neuronal morphology in the hippocampus. Moreover, our data indicate that these effects are

associated with the re-establishment of the HPA-axis activity.

An imbalance in adenosine receptors has been observed in multiple conditions,²¹ particularly with progressive aging,^{18,19} which has consequences to their modulatory effects.^{19,41} In the aged rat brain, adenosine A₁ receptor density is decreased,⁴⁷ particularly in hippocampus and cortex.¹⁸ However, A_{2A} receptor levels are differently affected: they decrease in striatum, but in contrast there is an increase in their expression in cortical and hippocampal areas.¹⁸ As we now show, the changes in adenosine receptor levels induced by MS, follow a close pattern to the one occurring in the aged brain, that is, an increase in A_{2A} and a decrease in A₁ receptor levels. The modifications observed are, however, restricted to the hippocampus, probably due to the changes in GR levels that are more profound in this brain area. Thus, as observed in aging,^{19,48} MS induces a decrease in GR levels, increasing the MR/GR ratio, an increase in plasma corticosterone levels and changes in adenosine receptor levels. Thereupon our data reinforce the hypothesis that stress is associated with an early aging in the hippocampal area.^{2,49} Different brain regions have a distinct vulnerability to stress due to the differential expression of GR and MR in the brain.⁵⁰ In the hippocampus, corticosterone is able to trigger signaling pathways activated by both GR and MR due to their particular high-affinity ratio for GR, which does not occur in other brain areas.⁵⁰ This confers to the hippocampus a particular susceptibility to stress effects and consequent deficits. Additional region-specific effects were reported previously, such as alterations in GABA_A receptor levels and MAP kinase activity.^{51,52}

We have observed a sustained increase in the plasmatic levels of corticosterone, a feature that is also shared with ageing.⁵³ Such an increase is usually associated to a downregulation in GR,^{11,54,55} as a way to limit their action. This is generally an isolated and reversible effect, reverted whenever the plasma levels of corticosterone return to baseline.⁵⁵ However, as we show, MS animals exhibit elevated plasma corticosterone levels throughout life and an associated sustained downregulation of GR in the hippocampus. These receptors regulate memory and synaptic plasticity.^{45,56} Accordingly, we found that LTP is impaired in MS animals and this is accompanied by a poorer performance in a spatial memory task, the MWM. The observed changes in synaptic plasticity can be related to the altered levels in GABA_A and AMPA receptors, reported here. Others have described that MS induces a decrease in markers of synaptic plasticity, such as NCAM or synaptophysin,⁴³ as well as in the levels of NMDAR2B, AMPA_{gluR1} and GluR2⁴⁴ in the hippocampus. Changes now observed in glutamate receptor levels had, however, no impact upon basal synaptic transmission, possibly because they are accompanied by a decrease in GABA_A receptors, which will result in a final compensatory balance in order to maintain homeostasis.

The observed impairments in LTP were overcome by blocking adenosine A_{2A} receptors. These receptors are known to have stimulatory effects on basal synaptic transmission in the hippocampus^{17,41} by promoting glutamate release,⁵⁷ and were recently shown to potentiate LTP when exogenously activated.⁵⁸ The protective effect of administering A_{2A} receptor antagonists *in vivo* has already been described.²¹ By contrast, we have observed before that, in particular conditions, the acute treatment of slices with SCH58261 may instead cause a LTP drop. This is particular to overexcitability conditions, such as ageing, in which LTP is enhanced^{29,59} due to an age-induced shift in A_{2A} receptor signaling.^{19,41} However, in more chronic patho-physiological situations, in which LTP is decreased, the SCH58261 is able to promote its restoration,⁶⁰ in accordance with what we now report for stress-induced deficits.

More importantly, the chronic administration of a selective antagonist, KW6002, for 1 month, clearly re-established the MS-driven impairment in LTP. However, the A_{2A} receptor antagonist did not alter LTP in CTR animals, whereas clearly promoting the recovery of the impaired LTP, but only in MS animals. This suggests that, rather than having a direct effect on glutamatergic transmission, A_{2A} receptors may be instead modulating the GR-mediated effects. Indeed, we have recent data showing the ability of A_{2A} receptors to influence GR transcriptional activity and nuclear translocation.⁶¹ Thus, the chronic blockade of A_{2A} receptor may decrease GR transcriptional activity and thereby the overall GR-driven effects.

Genetic deletion of A_{2A} receptors affects anxiety and aggressive behavior,⁶² and this constituted the first evidence that A_{2A} receptors could be implicated in stress. The subsequent report that A_{2A} receptor antagonists applied before and during a single episode of acute stress prevented synaptic loss,²² suggested that A_{2A} receptors overactivation could underlie the genesis of stress-induced changes. Nonetheless, the question whether this overactivation is a consequence of the stress paradigm or a triggering factor to the observed deficits has never been addressed before.

We now explored the possibility that blocking the action of A_{2A} receptors would restore pre-existing stress-associated impairments. The advantage of using KW6002 over other antagonists for A_{2A} receptors is its enhanced bioavailability, permeability to the brain blood barrier, having a longer half-life and high affinity and selectivity towards A_{2A} receptors.²⁷ Additionally, KW6002 has undergone clinical trials for Parkinson's and therefore its safety has been established.⁶³ We now report that oral administration of KW6002, for 1 month, to adult animals previously subjected to MS, reestablishes impaired hippocampal-dependent memory, synaptic plasticity and morphology, and reverts the anxious behavior. The learning ability of MS animals was restored by the treatment, as well as the retrieval, evaluated by the time spent in the previous retained platform

quadrant. This is associated with a re-establishment of the hippocampal CA1-induced LTP. The insertion of AMPA receptors containing GluR₁ subunit is a constitutive part of LTP induction⁶⁴ and is modulated by GR.⁶⁵ We found that GluR1-subunit is decreased by MS, which may explain the decreased LTP. Moreover, the LTP re-establishment is accompanied by a concomitant restoration of GluR1 levels upon KW6002 treatment. Accordingly, MS leads to a decrease in apical dendritic length, as described using other stress models,⁶⁶ but this structural effect is reverted by the blockade of A_{2A} receptors.

The HPA-axis maintains the physiological circadian oscillation of corticosterone levels, which reach their maximum at zenith (8 pm) and the minimum at nadir (8 am), for rodents.⁶⁷ The hippocampus is crucial in the negative feedback required to limit HPA-axis activation, particularly in stressful situations.^{1,2} However, this function can be compromised when glucocorticoid levels are persistently high as in chronic stress, aging or in psychopathologies.⁴⁸ The observation that the A_{2A} receptor antagonist was able to re-establish the decreased GR levels in the hippocampus lead us to test whether the observed effects were related to a modification of the HPA axis, by measuring the circadian levels of corticosterone in plasma. MS animals present not only higher plasmatic levels of corticosterone, but also an impaired circadian fluctuation. Corticosterone levels were chronically higher in MS animals and did not decrease along the night. This is probably associated to an impaired inhibition of the HPA-axis, which is consequence of a decrease in hippocampal GR levels. Interestingly, by blocking A_{2A} receptors, the basal levels of corticosterone were re-established, so as the circadian rhythm and the GR levels in the hippocampus. Altogether, these data suggest that A_{2A} receptors have a role in the regulation of the HPA-axis, either directly or by regulating hippocampal function. This effect may be due to interference with the release of corticotrophin-releasing hormone, adrenocorticotrophin, which is known to be affected by adenosine,⁶⁸ or by modulating glucocorticoids. The beneficial effect resulting from A_{2A} receptor antagonism may derive instead from a re-establishment of hippocampal excitability, which in turn would restore the inhibitory tonus onto the HPA-axis. Overall, the blockade of adenosine A_{2A} receptors by KW6002 has a beneficial effect in overcoming the hippocampal-related deficits induced by MS. Interestingly, this effect of KW6002 *in vivo* does not result from a decrease in A_{2A}R levels, which remain high in MS animals under KW6002. Indeed, it would be unlikely that KW6002 would cause a decrease in A_{2A}R levels as prolonged blockade of receptors usually leads to either no change or upregulation of receptor levels due to compensatory mechanisms following restraining from receptor activation by the endogenous ligand. Remarkably, the findings that blockade of A_{2A}R overcomes the synaptic and memory deficits associated to MS, strongly suggests that A_{2A} receptors

overactivation is the cause rather than the consequence of the herein reported changes associated with chronic stress.

In conclusion, our results show, for the first time, that the changes induced by stress are reverted by the *in vivo* blockade of A_{2A} receptors. Moreover, they imply a role of A_{2A}R in the HPA-axis regulation revealing that its blockade is efficient in re-establishing the compromised HPA-axis, which has clinical implications for the treatment of psychopathologies. This provides a potential alternative to the established therapies against stress-related pathologies, by targeting a modulatory system rather than interfering directly with neurotransmitters, and thereby limiting the associated side-effects.

Conflict of interest

The authors declare no conflict of interest.

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References

- 1 McEwen BS. Stress and hippocampal plasticity. *Annu Rev Neurosci* 1999; **22**: 105–122.
- 2 McEwen BS. Stress and the aging hippocampus. *Front Neuroendocrinol* 1999; **20**: 49–70.
- 3 McKinney WT. Animal models of depression: an overview. *Psychiatr Dev* 1984; **2**: 77–96.
- 4 Willner P. Validity, reliability and utility of the chronic mild stress model of depression: a 10-year review and evaluation. *Psychopharmacology (Berl)* 1997; **134**: 319–329.
- 5 Sullivan R, Wilson DA, Feldon J, Yee BK, Meyer U, Richter-Levin G et al. The International Society for Developmental Psychobiology annual meeting symposium: impact of early life experiences on brain and behavioral development. *Dev Psychobiol* 2006; **48**: 583–602.
- 6 Heim C, Nemeroff CB. The role of childhood trauma in the neurobiology of mood and anxiety disorders: preclinical and clinical studies. *Biol Psychiatry* 2001; **49**: 1023–1039.
- 7 Ladd CO, Huot RL, Thirivikraman KV, Nemeroff CB, Meaney MJ, Plotsky PM. Long-term behavioral and neuroendocrine adaptations to adverse early experience. *Prog Brain Res* 2000; **122**: 81–103.
- 8 Morris RG. Long-term potentiation and memory. *Philos Trans R Soc Lond B Biol Sci* 2003; **358**: 643–647.
- 9 de Kloet ER, Oitzl MS, Joels M. Stress and cognition: are corticosteroids good or bad guys? *Trends Neurosci* 1999; **22**: 422–426.
- 10 Amaral DG, Dent JA. Development of the mossy fibers of the dentate gyrus: I. A light and electron microscopic study of the mossy fibers and their expansions. *J Comp Neurol* 1981; **195**: 51–86.

- 11 Sapolsky RM, Meaney MJ. Maturation of the adrenocortical stress response: neuroendocrine control mechanisms and the stress hyporesponsive period. *Brain Res* 1986; **396**: 64–76.
- 12 Kaufman J, Plotsky PM, Nemeroff CB, Charney DS. Effects of early adverse experiences on brain structure and function: clinical implications. *Biol Psychiatry* 2000; **48**: 778–790.
- 13 Bakshi VP, Kalin NH. Corticotropin-releasing hormone and animal models of anxiety: gene-environment interactions. *Biol Psychiatry* 2000; **48**: 1175–1198.
- 14 Aisa B, Tordera R, Lasheras B, Del Rio J, Ramirez MJ. Cognitive impairment associated to HPA axis hyperactivity after maternal separation in rats. *Psychoneuroendocrinology* 2007; **32**: 256–266.
- 15 Anisman H, Zaharia MD, Meaney MJ, Merali Z. Do early-life events permanently alter behavioral and hormonal responses to stressors? *Int J Dev Neurosci* 1998; **16**: 149–164.
- 16 Lehmann J, Stohr T, Feldon J. Long-term effects of prenatal stress experiences and postnatal maternal separation on emotionality and attentional processes. *Behav Brain Res* 2000; **107**: 133–144.
- 17 Cunha RA, Johansson B, van der Ploeg I, Sebastiao AM, Ribeiro JA, Fredholm BB. Evidence for functionally important adenosine A_{2A} receptors in the rat hippocampus. *Brain Res* 1994; **649**: 208–216.
- 18 Cunha RA, Constantino MC, Sebastiao AM, Ribeiro JA. Modification of A₁ and A_{2A} adenosine receptor binding in aged striatum, hippocampus and cortex of the rat. *Neuroreport* 1995; **6**: 1583–1588.
- 19 Lopes LV, Cunha RA, Ribeiro JA. Increase in the number, G protein coupling, and efficiency of facilitatory adenosine A_{2A} receptors in the limbic cortex, but not striatum, of aged rats. *J Neurochem* 1999; **73**: 1733–1738.
- 20 Rebola N, Sebastiao AM, de Mendonca A, Oliveira CR, Ribeiro JA, Cunha RA. Enhanced adenosine A_{2A} receptor facilitation of synaptic transmission in the hippocampus of aged rats. *J Neurophysiol* 2003; **90**: 1295–1303.
- 21 Cunha RA. Neuroprotection by adenosine in the brain: from A(1) receptor activation to A (2A) receptor blockade. *Purinergic Signal* 2005; **1**: 111–134.
- 22 Cunha GM, Canas PM, Oliveira CR, Cunha RA. Increased density and synapto-protective effect of adenosine A_{2A} receptors upon sub-chronic restraint stress. *Neuroscience* 2006; **141**: 1775–1781.
- 23 Belanoff JK, Gross K, Yager A, Schatzberg AF. Corticosteroids and cognition. *J Psychiatr Res* 2001; **35**: 127–145.
- 24 Belanoff JK, Kalehzan M, Sund B, Fleming Ficek SK, Schatzberg AF. Cortisol activity and cognitive changes in psychotic major depression. *Am J Psychiatry* 2001; **158**: 1612–1616.
- 25 Daniels WM, Pietersen CY, Carstens ME, Stein DJ. Maternal separation in rats leads to anxiety-like behavior and a blunted ACTH response and altered neurotransmitter levels in response to a subsequent stressor. *Metab Brain Dis* 2004; **19**: 3–14.
- 26 Lopes LV, Marvin-Guy LF, Fuerholz A, Affolter M, Ramadan Z, Kussmann M et al. Maternal deprivation affects the neuromuscular protein profile of the rat colon in response to an acute stressor later in life. *J Proteomics* 2008; **71**: 80–88.
- 27 Yang M, Soohoo D, Soelaiman S, Kalla R, Zablocki J, Chu N et al. Characterization of the potency, selectivity, and pharmacokinetic profile for six adenosine A_{2A} receptor antagonists. *Naunyn Schmiedeberg Arch Pharmacol* 2007; **375**: 133–144.
- 28 Morris RG, Garrud P, Rawlins JN, O'Keefe J. Place navigation impaired in rats with hippocampal lesions. *Nature* 1982; **297**: 681–683.
- 29 Diogenes MJ, Costenla AR, Lopes LV, Jeronimo-Santos A, Sousa VC, Fontinha BM et al. Enhancement of LTP in aged rats is dependent on endogenous BDNF. *Neuropsychopharmacology* 2011; **36**: 1823–1836.
- 30 Pellow S, Chopin P, File SE, Briley M. Validation of open:closed arm entries in an elevated plus-maze as a measure of anxiety in the rat. *J Neurosci Methods* 1985; **14**: 149–167.
- 31 Gibb R, Kolb B. A method for vibratome sectioning of Golgi-Cox stained whole rat brain. *J Neurosci Methods* 1998; **79**: 1–4.
- 32 Keuker JI, Vollmann-Honsdorf GK, Fuchs E. How to use the optical fractionator: an example based on the estimation of neurons in the hippocampal CA1 and CA3 regions of tree shrews. *Brain Res Brain Res Protoc* 2001; **7**: 211–221.
- 33 Madeira MD, Pereira A, Cadete-Leite A, Paula-Barbosa MM. Estimates of volumes and pyramidal cell numbers in the prelimbic subarea of the prefrontal cortex in experimental hypothyroid rats. *J Anat* 1990; **171**: 41–56.
- 34 Glaser EM, Van der Loos H. Analysis of thick brain sections by obverse-reverse computer microscopy: application of a new, high clarity Golgi-Nissl stain. *J Neurosci Methods* 1981; **4**: 117–125.
- 35 Paxinos G, Watson C. *The Rat Brain in Stereotaxic Coordinates*. 3rd edn. Academic Press: Waltham, MA, USA, 1998.
- 36 Palomero-Gallagher N, Zilles K. The rat isocortex. In: Paxinos G (ed). *The Rat Nervous System*. Academic Press: San Diego, CA, USA, 2004; 728–760.
- 37 Gundersen HJ, Bagger P, Bendtsen TF, Evans SM, Korbo L, Marcussen N et al. The new stereological tools: disector, fractionator, nucleator and point sampled intercepts and their use in pathological research and diagnosis. *APMIS* 1988; **96**: 857–881.
- 38 Palacios SD, Pak K, Rivkin AZ, Kayali AG, Austen D, Aletsee C et al. Role of p38 mitogen-activated protein kinase in middle ear mucosa hyperplasia during bacterial otitis media. *Infect Immun* 2004; **72**: 4662–4667.
- 39 Lowry OH, Rosebrough NJ, Farr AL, Randall RJ. Protein measurement with the Folin phenol reagent. *J Biol Chem* 1951; **193**: 265–275.
- 40 Bradford MM. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal Biochem* 1976; **72**: 248–254.
- 41 Lopes LV, Cunha RA, Ribeiro JA. Cross talk between A(1) and A(2A) adenosine receptors in the hippocampus and cortex of young adult and old rats. *J Neurophysiol* 1999; **82**: 3196–3203.
- 42 Hockemeyer J, Burbiel JC, Muller CE. Multigram-scale syntheses, stability, and photoreactions of A_{2A} adenosine receptor antagonists with 8-styrylxanthine structure: potential drugs for Parkinson's disease. *J Org Chem* 2004; **69**: 3308–3318.
- 43 Aisa B, Elizalde N, Tordera R, Lasheras B, Del Rio J, Ramirez MJ. Effects of neonatal stress on markers of synaptic plasticity in the hippocampus: implications for spatial memory. *Hippocampus* 2009; **19**: 1222–1231.
- 44 Pickering C, Gustafsson L, Cebere A, Nylander I, Liljequist S. Repeated maternal separation of male Wistar rats alters glutamate receptor expression in the hippocampus but not the prefrontal cortex. *Brain Res* 2006; **1099**: 101–108.
- 45 Joels M. Corticosteroid effects in the brain: U-shape it. *Trends Pharmacol Sci* 2006; **27**: 244–250.
- 46 Janusz CA, Berman RF. The A₂-selective adenosine analog, CGS 21680, depresses locomotor activity but does not block amygdala kindled seizures in rats. *Neurosci Lett* 1992; **141**: 247–250.
- 47 Meerlo P, Roman V, Farkas E, Keijsers JN, Nyakas C, Luiten PG. Ageing-related decline in adenosine A₁ receptor binding in the rat brain: an autoradiographic study. *J Neurosci Res* 2004; **78**: 742–748.
- 48 Pardon MC, Rattray I. What do we know about the long-term consequences of stress on ageing and the progression of age-related neurodegenerative disorders? *Neurosci Biobehav Rev* 2008; **32**: 1103–1120.
- 49 Miller DB, O'Callaghan JP. Aging, stress and the hippocampus. *Ageing Res Rev* 2005; **4**: 123–140.
- 50 Reul JM, de Kloet ER. Two receptor systems for corticosterone in rat brain: microdistribution and differential occupation. *Endocrinology* 1985; **117**: 2505–2511.
- 51 Gruen RJ, Wenberg K, Elahi R, Friedhoff AJ. Alterations in GABA_A receptor binding in the prefrontal cortex following exposure to chronic stress. *Brain Res* 1995; **684**: 112–114.
- 52 Meller E, Shen C, Nikolao TA, Jensen C, Tsimberg Y, Chen J et al. Region-specific effects of acute and repeated restraint stress on the phosphorylation of mitogen-activated protein kinases. *Brain Res* 2003; **979**: 57–64.
- 53 Mizoguchi K, Ikeda R, Shoji H, Tanaka Y, Maruyama W, Tabira T. Aging attenuates glucocorticoid negative feedback in rat brain. *Neuroscience* 2009; **159**: 259–270.
- 54 Sapolsky RM, Meaney MJ, McEwen BS. The development of the glucocorticoid receptor system in the rat limbic brain. III. Negative-feedback regulation. *Brain Res* 1985; **350**: 169–173.

- 55 Sapolsky RM, Krey LC, McEwen BS. Stress down-regulates corticosterone receptors in a site-specific manner in the brain. *Endocrinology* 1984; **114**: 287–292.
- 56 Sousa N, Cerqueira JJ, Almeida OF. Corticosteroid receptors and neuroplasticity. *Brain Res Rev* 2008; **57**: 561–570.
- 57 Lopes LV, Cunha RA, Kull B, Fredholm BB, Ribeiro JA. Adenosine A(2A) receptor facilitation of hippocampal synaptic transmission is dependent on tonic A(1) receptor inhibition. *Neuroscience* 2002; **112**: 319–329.
- 58 Dias RB, Ribeiro JA, Sebastiao AM. Enhancement of AMPA currents and GluR1 membrane expression through PKA-coupled adenosine A(2A) receptors. *Hippocampus* 2012; **22**: 276–291.
- 59 Costenla AR, Diogenes MJ, Canas PM, Rodrigues RJ, Nogueira C, Maroco J *et al*. Enhanced role of adenosine A(2A) receptors in the modulation of LTP in the rat hippocampus upon ageing. *Eur J Neurosci* 2011; **34**: 12–21.
- 60 Rebola N, Carta M, Lanore F, Blanchet C, Mulle C. NMDA receptor-dependent metaplasticity at hippocampal mossy fiber synapses. *Nat Neurosci* 2011; **14**: 691–693.
- 61 Batalha VL, Hamdane M, Sebastião AM, Buée L, Blum D, Lopes LV. Modulation of glucocorticoid receptor (GR) transcriptional activity by adenosine A2A receptors: consequences for stress response. *Champalimaud Neurosci Symp* 2011; http://symposium.neuro.fchampalimaud.org/files/CNP_symp_Abstracts_2.pdf.
- 62 Ledent C, Vaugeois JM, Schiffmann SN, Pedrazzini T, El Yacoubi M, Vanderhaeghen JJ *et al*. Aggressiveness, hypoalgesia and high blood pressure in mice lacking the adenosine A2a receptor. *Nature* 1997; **388**: 674–678.
- 63 Hauser RA, Hubble JP, Truong DD. Randomized trial of the adenosine A(2A) receptor antagonist istradefylline in advanced PD. *Neurology* 2003; **61**: 297–303.
- 64 Andrasfalvy BK, Smith MA, Borchardt T, Sprengel R, Magee JC. Impaired regulation of synaptic strength in hippocampal neurons from GluR1-deficient mice. *J Physiol* 2003; **552**(Part 1): 35–45.
- 65 Martin S, Henley JM, Holman D, Zhou M, Wiegert O, van Spronsen M *et al*. Corticosterone alters AMPAR mobility and facilitates bidirectional synaptic plasticity. *PLoS One* 2009; **4**: e4714.
- 66 Bessa JM, Ferreira D, Melo I, Marques F, Cerqueira JJ, Palha JA *et al*. The mood-improving actions of antidepressants do not depend on neurogenesis but are associated with neuronal remodeling. *Mol Psychiatry* 2009; **14**: 764–773, 739.
- 67 Allen C, Kendall JW. Maturation of the circadian rhythm of plasma corticosterone in the rat. *Endocrinology* 1967; **80**: 926–930.
- 68 Anand-Srivastava MB, Cantin M, Gutkowska J. Adenosine regulates the release of adrenocorticotrophic hormone (ACTH) from cultured anterior pituitary cells. *Mol Cell Biochem* 1989; **89**: 21–28.

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