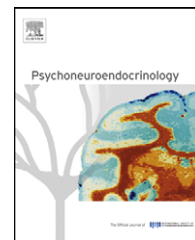




available at www.sciencedirect.com



journal homepage: www.elsevier.com/locate/psyneuen



Mifepristone decreases depression-like behavior and modulates neuroendocrine and central hypothalamic–pituitary–adrenocortical axis responsiveness to stress

Aynara C. Wulsin^{a,1}, James P. Herman^{a,b,2}, Matia B. Solomon^{a,*}

^aDepartment of Psychiatry, University of Cincinnati, College of Medicine, Cincinnati, OH 45267, United States

^bNeuroscience Program, University of Cincinnati, College of Medicine, Cincinnati, OH 45267, United States

Received 4 August 2009; received in revised form 16 January 2010; accepted 19 January 2010

KEYWORDS

Glucocorticoids;
Forced swim test;
Depression;
Medial prefrontal cortex;
RU486;
HPA axis;
c-Fos;
Immunohistochemistry;
Neuronal activation

Summary Glucocorticoid dyshomeostasis is observed in a proportion of depressed individuals. As a result, glucocorticoid receptor (GR) antagonists are currently being tested as potential anti-depressants. The current study was designed to test the efficacy of mifepristone, a GR antagonist, in mitigating behavioral, neuroendocrine and central nervous system (CNS) responses to an acute stressor. Adult male rats were treated for 5 days with mifepristone (10 mg/kg) and then exposed to the forced swim test (FST). Treatment with mifepristone decreased immobility and increased swimming (but not climbing) behavior in the FST, consistent with anti-depressant action. In addition, mifepristone dampened the ACTH response to FST exposure. In the CNS, mifepristone increased c-Fos expression in all subdivisions of the medial prefrontal cortex (mPFC) and decreased neuronal activity in some subdivisions of the hippocampus including the CA2, CA3, and hilus region of the dentate gyrus in animals exposed to FST. In contrast, mifepristone increased neuronal activity in the ventral subiculum (output region of the hippocampus) and decreased c-Fos expression in the central amygdala (CeA) in animals exposed to FST. These data suggest that anti-depressant efficacy and perhaps HPA dampening properties of RU486 are related to alterations in key limbic circuits mediating CNS stress responses, resulting in enhanced stress inhibition (via the mPFC and ventral subiculum) as well as decreased stress excitation (central amygdala). Overall the data suggest that drugs targeting the glucocorticoid receptor may ameliorate stress dysfunction associated with depressive illness.

© 2010 Elsevier Ltd. All rights reserved.

* Corresponding author at: University of Cincinnati, Genome Research Institute, 2170 E. Galbraith Rd. Room 216, Cincinnati, OH 45237-0506, United States. Tel.: +1 513 558 3025; fax: +1 513 558 9104.

E-mail addresses: aynara.chavez@gmail.com (A.C. Wulsin), james.herman@uc.edu (J.P. Herman), matia.solomon@uc.edu (M.B. Solomon).

¹ Address: University of Cincinnati, Genome Research Institute, 2170 E. Galbraith Rd. Bldg E. Room 216, Cincinnati, OH 45237-0506, United States. Tel.: +1 513 558 3025; fax: +1 513 558 9104.

² Address: University of Cincinnati, Genome Research Institute, 2170 E. Galbraith Rd. Bldg A. Room 145, Cincinnati, OH 45237-0506, United States. Tel.: +1 513 558 4813; fax: +1 513 558 9104.

1. Introduction

Dysregulation of the hypothalamic pituitary adrenal (HPA) axis, manifested by elevation in circulating glucocorticoids (hypercortisolemia), is associated with affective disorders including major depression (Gold and Chrousos, 1999). It is hypothesized that hypercortisolemia is caused by disruptions in glucocorticoid-mediated negative feedback. The glucocorticoid-mediated negative feedback protects against prolonged activation of this axis, thereby preventing many of the adverse psychological and physiological consequences of glucocorticoid hypersecretion. Notably, decreased hypercortisolemia is commonly observed with successful anti-depressant treatment (Delbende et al., 1991; Reul et al., 1994; Pariante, 2003) implicating aberrant glucocorticoid signaling in depressive pathology. As such, the glucocorticoid receptor (GR) is currently a target for development of new anti-depressant therapies (Thomson and Craighead, 2008).

Mifepristone is a potent GR and progesterone receptor antagonist that is known to have anti-depressant effects following relatively brief treatment in humans (4–8 days) (Belanoff et al., 2001). The use of mifepristone in individuals with elevated glucocorticoids as a result of chronic stress or in the case of Cushing's syndrome may be particularly advantageous as preliminary blockade of GR can serve as a barrier against the deleterious effects of excess glucocorticoid production. An additional advantage of GR antagonists as discussed in Belanoff et al. (2001) and Thomson and Craighead (2008) is that prolonged antagonism of GR may actually lead to an up-regulation in GR in critical hypothalamic and limbic structures, thereby enhancing the GR negative feedback control of the HPA axis. Behavioral testing in rodents corroborates the efficacy of mifepristone or other GR antagonists (ORG34116) to ameliorate depression-like behaviors in the forced swim test (FST) (de Kloet et al., 1988; Bachmann et al., 2005). The FST, described originally by (Porsolt et al., 1977) is among the most widely used model for assessing pharmacological anti-depressant efficacy. An effective anti-depressant decreases immobility and increases active behaviors such as swimming and/or climbing in the FST (Cryan et al., 2005a). Previous studies have found that mifepristone (10 mg/kg, s.c.) administered 60 min prior to FST exposure, reverses the stress-induced increase in immobility normally observed in both male and female rats exposed to maternal separation in early life (Aisa et al., 2007, 2008). In addition, 4-day treatment of mifepristone normalizes the stress-induced reductions in hippocampal neurogenesis (Oomen et al., 2007). More importantly, this study demonstrated that mifepristone alone has no effect on neurogenesis, suggesting that the normalizing effect of the drug is evident during conditions of elevated glucocorticoids. Collectively, these findings suggest that mifepristone prevents stress-induced decreases in neuroplasticity as well as stress-induced increases in depression-like behaviors.

To our knowledge, there are no published studies that have extensively examined the effects of mifepristone on stress-induced neuronal activation in depression-related and stress-sensitive brain regions. Thus, the aim of the present study was to assess the neuroendocrine and central impact of mifepristone treatment in rats exposed to an acute stressor. This was accomplished by measuring adrenocorticotropin hormone (ACTH) and corticosterone concentrations as well

as Fos induction following FST exposure. Based on the reported effects of anti-depressants on specific neural regions in depressed patients (Arce et al., 2008; Ishizaki et al., 2008; Kukolja et al., 2008) we predicted that the anti-depressant-like effect of mifepristone would be associated with alterations in forebrain regions responsible for regulation of stress responding.

2. Materials and methods

2.1. Subjects

Male Sprague Dawley rats (Harlan Sprague Dawley, Indianapolis, IN; 250–300 G) were housed individually in standard rat shoebox cages and acclimated to the laboratory conditions for 1 week before initiation of the experiment. Rats were maintained in a temperature- and humidity-controlled room (lights on 06:00 to 18:00) with food and water available *ad libitum*. All experimental procedures and protocols were conducted in accordance with the National Institutes of Health Guidelines for the Care and Use of Animals and approved by the University of Cincinnati Institutional Animal Care and Use Committee.

2.2. Drug treatment

In Experiment 1, 26 animals were matched by body weight and were divided into three groups, and administered a single daily injection of mifepristone ($n = 9$) (Sigma–Aldrich 10 mg/kg s.c. dissolved in propylene glycol), imipramine ($n = 9$) (Sigma–Aldrich 10 mg/kg i.p. dissolved in saline) or vehicle ($n = 8$) (propylene glycol s.c.) for 5 days. Imipramine is known to have significant anti-depressant effects in the FST and was included as a positive control (Morley-Fletcher et al., 2004). On the fifth day, 1 h after the last injection, animals were exposed to the FST as described below. In Experiment 2, 36 animals were matched by body weight and divided into two groups and received mifepristone (10 mg/kg in propylene glycol) ($n = 20$) or the vehicle control, propylene glycol ($n = 16$) as described in Experiment 1. On the fifth day, 1 h after last injection, animals were exposed to the FST ($n = 10$ for mifepristone; $n = 10$ for vehicle). The remaining rats mifepristone ($n = 10$) and vehicle ($n = 6$) served as non-stressed controls. The mifepristone dose was selected based on successful anti-depressant effects previously observed in rats (Aisa et al., 2007, 2008).

2.3. Behavior

Forced swim test. The FST test was chosen as a way to assess the effects of mifepristone on depression-like behavior and as an acute stressor to activate the HPA axis. The modified FST was conducted according to the methodology described by Cryan et al. (2005b) which differs from the classical Porsolt FST (Porsolt et al., 1977), in that animals are only exposed to the FST once for 10 min. The behavioral apparatus was a Plexiglas cylinder 45 cm high and 20 cm in diameter filled with 31 cm of water (30–33 °C). Rats were placed in the cylinder for 10 min and the session was videotaped. Scoring was done by two independent observers blind to the treatment conditions. The behavior was scored every 5 s based on the criteria listed below. The total counts of each behavior during the 10 min

testing session was summed for each animal and averaged within each treatment group. The behaviors scored are defined as follows: (i) climbing – rapid movement of limbs in and out of the water with the body parallel to the apparatus with, (ii) diving, (iii) swimming – moving limbs in an active manner and making circular movements around the apparatus; and immobility – rat not making any active movements or floating in the water without struggling.

2.4. Blood collection

Tail blood was collected by tail vein nick 15 and 90 min after the end of FST and in control animals not subjected to FST at the same time intervals. Blood samples were collected into tubes containing EDTA and were immediately placed on ice. Plasma was obtained by centrifugation ($1500 \times g$, 15 min, 4°C) and stored at -20°C for subsequent analysis of plasma ACTH and corticosterone.

2.5. Organ collection

In order to determine the effects of mifepristone on stress-responsive and reproductive organs, testicles, adrenal and thymus glands were removed and cleaned from each animal for weight determination.

2.6. Radioimmunoassay

Plasma corticosterone levels were measured using ^{125}I RIA kits (MP Biomedicals, Inc., Orangerburg, NY). Plasma ACTH concentrations were determined by an RIA that used a specific antiserum generously donated by Dr. William Engeland (University of Minnesota, Minneapolis, MN) at a dilution of 1:120,000, with ^{125}I ACTH (Amersham Biosciences, Piscataway, NJ) as labeled tracer (Jasper and Engeland, 1991).

2.7. Immunohistochemistry

Ninety minutes following FST exposure, animals were anesthetized with an overdose of sodium pentobarbital and intracardially perfused with 100 mL of 0.9% saline followed by 200 mL of 3.7% Formaldehyde in 0.1 M phosphate buffer (PBS), pH 7.6. Brains were subsequently removed and post-fixed using the same fixative for 24 h at 4°C before being transferred and stored for 2 days in 0.1 M PBS containing 30% sucrose. Coronal sections were cut at $35\ \mu\text{m}$ with a freezing microtome and alternate sections collected into wells containing cryoprotectant solution. Brain sections were transferred from the cryoprotectant solution to 0.1 M PBS solution. After this step and all subsequent incubations, sections were rinsed 3×5 min in PBS. Subsequent incubations were (1) rabbit polyclonal c-Fos antibody (1:5000, Santa Cruz Biotechnology) in 0.05 M solution of PBS containing 0.25% bovine serum albumin and 0.5% Triton X-100 overnight at room temperature; (2) biotinylated goat anti-rabbit (1:500; Vector laboratories, Burlingame, CA) in 0.05 M solution of PBS containing 0.25% bovine serum albumin and 0.5% Triton X-100 for 1 h at room temperature; (3) avidin-biotin horseradish peroxidase complex (1:800; Vectastain ABC elite Kit, Vector Laboratories) in 0.05 M solution of PBS containing 0.25% bovine serum albumin for 1 h at room temperature; (4) ABC-horseradish peroxidase complex was visualized with

3,3'-diaminobenzidine (Sigma) that was dissolved in a solution containing Tris-NaCl and 0.09% hydrogen peroxide for 15 min. Sections were mounted on gelatinized slides, allowed to dry, dehydrated with alcohol and xylene and coverslipped.

2.8. Data analysis

2.8.1. Cell counting

For analysis of Fos positive immunoreactive nuclei, digital images of regions of interest were captured and subjected to quantitative analysis of cell counts. The number of Fos-immunoreactive cell nuclei was determined from thresholded images using the Scion Image software. A uniform threshold (based on a pre-defined threshold function in Scion Image) was applied to all images in a given brain region and the average optical density was automatically calculated and expressed as mean optical density. The final cell counts were expressed as the number of positive nuclei per unit area (mm^2). The shape and size of each brain region studied were defined according to the boundaries outlined in Paxinos and Watson (1998) rat stereotaxic atlas as illustrated in Fig. 1. A total of 2–3 images (including both right and left hemispheres) were analyzed for each region and averaged to produce a mean cell count/area for each region. We analyzed c-Fos activation in three areas of the medial prefrontal cortex (anterior cingulate, infralimbic and prelimbic), five subdivisions of the hippocampus (CA1, CA2, CA3, dentate gyrus, hilus and ventral subiculum), three amygdala subdivisions (central amygdala, medial amygdala and basolateral amygdala), three subdivisions of the bed nucleus of the stria terminalis (anteroventral, anterior lateral and posterior medial), ventral lateral septum, paraventricular nucleus of the hypothalamus, and paraventricular thalamic nucleus.

2.9. Statistical analysis

Behavioral data were analyzed with one-way ANOVA or *t*-test where applicable. Hormonal data were analyzed using a three-way repeated measures ANOVA with stress and drug as between-subjects factors and time as the within or repeating factor. For immunohistochemical analysis, differences in overall c-Fos content were analyzed as a two-way ANOVA with drug and stress as between-subjects factors. Terminal measures including adrenals, thymus, body weight and testes were also analyzed using an independent sample *t*-test. Note, the terminal measures were analyzed regardless of stress because an acute 10 min swim stress is not sufficient to induce changes in these parameters; therefore the data were analyzed with respects to drug administration alone. When necessary data that violated Levene's homogeneity of variance were log transformed followed by the appropriate statistical analyses. Fisher's LSD post hoc tests were used to compare individual group differences. For all data $p \leq 0.05$ denotes statistical significance.

3. Results

3.1. Behavioral analysis

3.1.1. Experiment 1

Mifepristone and imipramine significantly increased swimming in the FST ($F(2,23) = 6.18$, $p < 0.01$) relative to vehicle

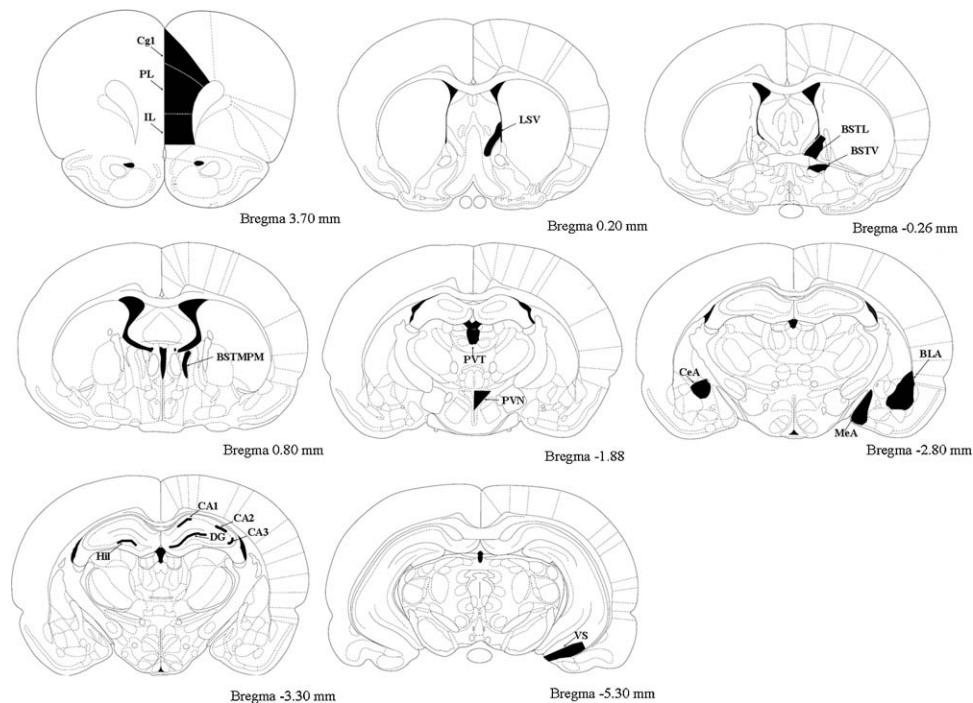


Figure 1 Templates and relative sizes of each brain nucleus analyzed for c-Fos based on the Paxinos and Watson rat brain atlas. *Abbreviations:* mPFC, medial prefrontal cortex; IL, infralimbic; PL, prelimbic; CG1, anterior cingulate; vLS, ventral lateral setum; hippocampal subdivisions include: CA1; CA2; CA3, DG, dentate gyrus; hil; hilus; VS, ventral subiculum; amygdaloid complex: CeA, central amygdala; MeA, medial amygdala; BLA, basolateral amygdala; BST, Bed nucleus of the stria terminalis: vBST, anteroventral BST; PMBNST, posterior medial BST; lBST, lateral BST; PVN paraventricular nucleus of the hypothalamus; PVT, paraventricular nucleus of the thalamus.

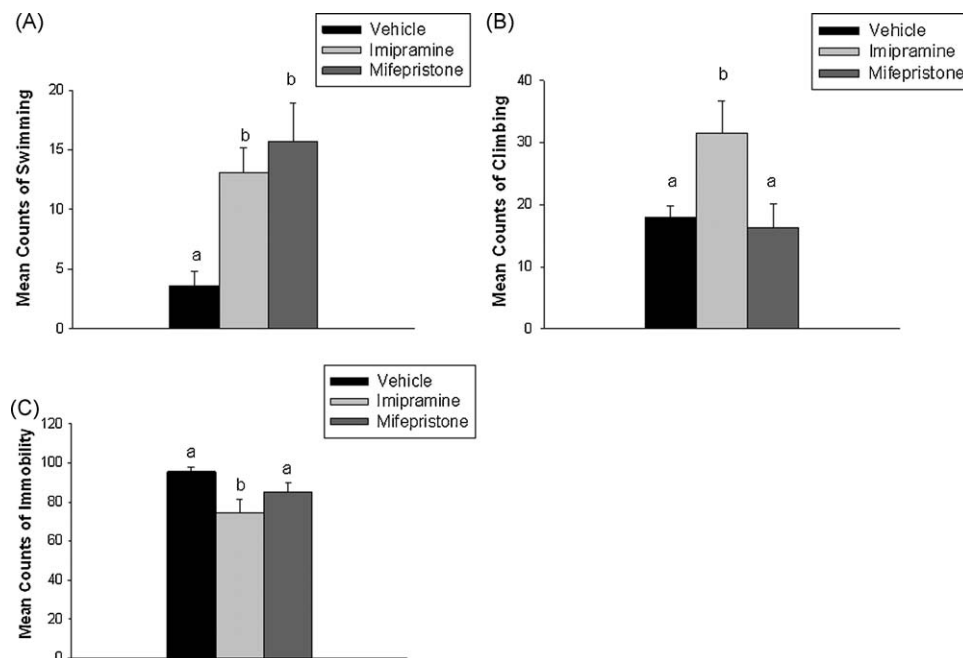


Figure 2 Mifepristone and imipramine significantly increased swimming relative to vehicle (A). Imipramine significantly increased climbing relative to mifepristone and vehicle (B). Imipramine significantly decreased immobility in the FST compared with mifepristone and vehicle (C). Data are represented as mean \pm S.E.M., $n = 8-9$ per group. Non-shared letters denotes statistical significance, $p < 0.05$.

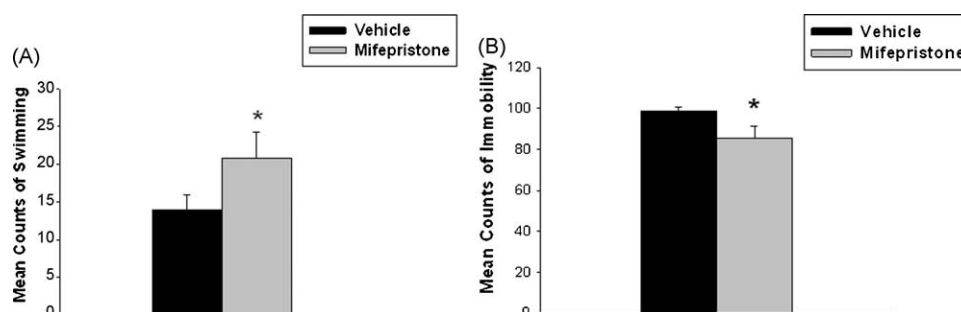


Figure 3 Mifepristone significantly increased swimming (A) and decreased immobility significantly compared with vehicle (B). Data are represented as mean \pm S.E.M., $n = 10$ per group. * $p < 0.05$ vs. vehicle treated groups.

(Fig. 2A). Imipramine significantly increased climbing in the FST ($F(2,23) = 4.35$, $p < 0.05$) relative to both mifepristone and vehicle. There was however no significant difference in climbing between mifepristone and vehicle treated animals (Fig. 2B). There was a trend for mifepristone to decrease time spent immobile but imipramine significantly decreased time spent immobile in the FST ($F(2,23) = 4.45$, $p < 0.05$) compared with vehicle. There was no significant difference in immobility between imipramine and mifepristone treated animals (Fig. 2C).

3.1.2. Experiment 2

Animals administered mifepristone displayed significantly more swimming ($t(18) = 2.57$, $p = 0.05$) (Fig. 3A) and less immobility ($t(18) = 2.55$, $p < 0.05$) (Fig. 3B) in the FST compared with vehicle treated animals, suggesting a decrease in depression-like behavior in the mifepristone group. Consistent with Experiment 1, there were no differences in climbing behaviors between animals treated with mifepristone and vehicle, $p > 0.05$ (data not shown).

3.2. Hormonal analysis ACTH

There was a significant main effect of stress ($F(1,32) = 33.85$, $p < 0.01$), drug ($F(1,32) = 35.14$, $p < 0.01$) and time ($F(1,71) = 71.55$, $p < 0.01$) on ACTH responses. In addition, there was a significant stress \times time interaction ($F(1,71) = 4.06$, $p = 0.05$), and drug \times time interaction ($F(1,71) = 30.45$, $p < 0.01$). Specifically, at 15 min animals exposed to FST exhibited significantly higher ACTH concentrations relative to non-stressed controls. At the 15 min time-point, the FST-mifepristone group had lower ACTH concentrations relative to the FST vehicle animals. There were no differences among groups at 90 min (Fig. 4).

3.3. Hormonal analysis corticosterone

There was a significant main effect of stress on corticosterone concentrations ($F(1,32) = 178.77$, $p < 0.01$). There was no significant main effect of drug on corticosterone responses; however, there was a significant main effect of time ($F(1,71) = 57.8$, $p < 0.01$) and significant stress \times time ($F(1,71) = 5.46$, $p < 0.05$) drug \times time ($F(1,71) = 38.64$, $p < 0.01$) and stress \times drug \times time interactions ($F(1,71) = 4.05$, $p = 0.05$). At 15 min, animals exposed to FST displayed higher corticosterone concentrations regardless of drug treat-

ment. At 90 min the animals exposed to FST continued to mount a higher corticosterone response relative to their non-stressed counterparts. Of note, the FST-mifepristone group displayed significantly higher corticosterone at 90 min compared with all other groups (Fig. 5) consistent with deficits in intermediate feedback regulation of the HPA axis.

3.4. Immunohistochemical analyses

3.4.1. Medial prefrontal cortex

Similar patterns of Fos activation were observed in all subdivisions of the medial prefrontal cortex. There was a significant main effect of stress on c-Fos expression in the AC ($F(1,28) = 19.42$, $p < 0.01$), PL ($F(1,28) = 23.69$, $p < 0.01$), and IL ($F(1,28) = 19.78$, $p < 0.01$), a significant main effect of drug only within the AC ($F(1,28) = 6.347$, $p < 0.01$) and a significant stress \times drug interaction in the AC ($F(1,28) = 7.62$, $p < 0.01$); PL ($F(1,28) = 10.24$, $p < 0.01$), IL ($F(1,28) = 10.53$, $p < 0.01$). In all cases, post hoc analyses revealed greater numbers of c-Fos labeled neurons in the FST-mifepristone group relative to all other groups. Within the infralimbic and prelimbic regions, the FST vehicle group had greater c-Fos activity relative to the No FST-mifepristone treated group only (Fig. 6).

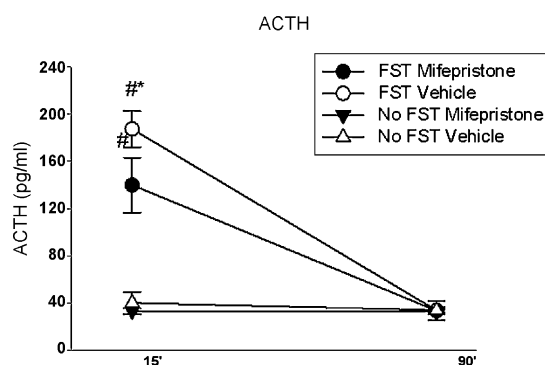


Figure 4 FST significantly increased ACTH levels at the 15 min time-point, regardless of drug treatment. However, animals exposed to FST and treated with mifepristone displayed decreased ACTH concentrations in response to FST exposure relative to the FST-vehicle treated animals, suggesting a dampening of the ACTH response in the FST-mifepristone group. Data are represented as mean \pm S.E.M., $n = 6$ –10 per group. # $p < 0.05$ vs. no FST group, * $p < 0.05$ vs. all other groups.

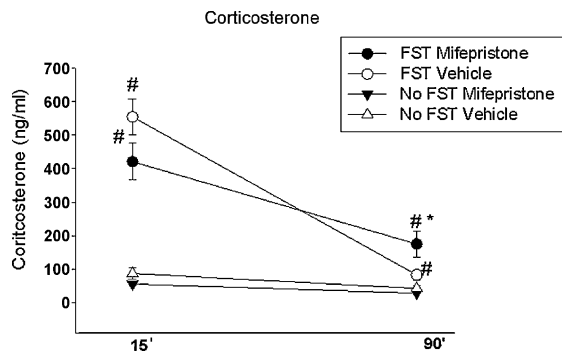


Figure 5 FST significantly increased corticosterone levels at the 15 min time-point, regardless of drug treatment. There was however a strong trend for mifepristone to decrease the corticosterone response to FST exposure relative to the respective vehicle treated group. At the 90 min time-point animals exposed to FST continued to display increased corticosterone levels relative to the animals not exposed to FST. At the 90 min time-point the FST-mifepristone group exhibited higher corticosterone relative to all other groups. Data are represented as mean \pm S.E.M., $n = 6-10$ per group. [#] $p < 0.05$ vs. no FST group, ^{*} $p < 0.05$ vs. all other groups.

3.4.2. Hippocampus

We examined five regions of the hippocampus: CA1, CA2, CA3, dentate gyrus (DG), and the hilus (i.e., CA4). There was a significant main effect of stress on c-Fos expression in the CA1 ($F(1,29) = 10.56$, $p < 0.01$); CA2 ($F(1,30) = 10.99$, $p < 0.01$); CA3 ($F(1,31) = 13.18$, $p < 0.01$); DG ($F(1,30) = 34.59$, $p < 0.01$); and hilus ($F(1,30) = 12.52$, $p < 0.01$) with animals exposed to FST displaying higher levels of c-Fos activation

compared with No FST group. There was no significant main effect of drug on c-Fos expression within any of the subdivisions. However, there was a significant stress \times drug interaction in the CA1 ($F(1,29) = 4.66$, $p < 0.05$); CA2 ($F(1,30) = 9.12$, $p < 0.01$); CA3 ($F(1,31) = 8.61$, $p < 0.01$); and hilus ($F(1,33) = 4.52$, $p < 0.05$) regions. Specifically, the FST-mifepristone group had significantly lower c-Fos expression in the CA2, CA3 and hilus regions compared with the respective vehicle treated group and within the CA1, the FST vehicle group had significantly higher c-Fos expression relative to all other groups. Of note, there was a trend for the FST-mifepristone group to have lower c-Fos expression within the CA1. Refer to Fig. 7A–C for data illustration of CA1, CA2 and CA3 regions and Fig. 7D and E for the dentate gyrus and hilus subdivisions of the hippocampus. For a representative photomicrograph of c-Fos immunohistochemistry of the CA3 region, refer to Fig. 8.

3.4.3. Ventral subiculum

There was a significant main effect of stress on c-Fos activation in the Vsub ($F(1,34) = 4.75$, $p < 0.01$), a significant main effect of drug ($F(1,34) = 15.03$, $p < 0.01$) and significant stress \times drug interaction ($F(1,34) = 3.84$, $p < 0.05$). Unlike the dampened c-Fos response in the FST-mifepristone group in observed in the CA2, CA3 and hilus, the FST-mifepristone group had the greatest amount of c-Fos activity relative to all other groups in the Vsub (Fig. 9).

3.4.4. Amygdala

There was a significant main effect of stress ($F(1,31) = 63.15$, $p < 0.01$), significant main effect of drug ($F(1,31) = 4.37$, $p < 0.05$) and a significant stress \times drug interaction ($F(1,31) = 5.41$, $p < 0.05$) in the central amygdala (CeA).

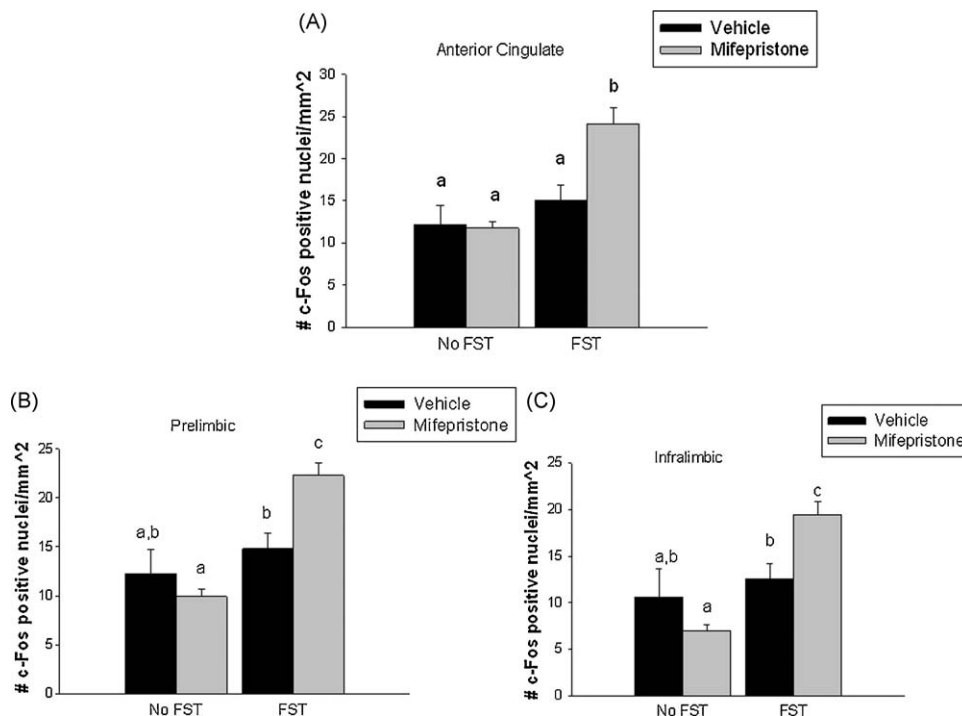


Figure 6 Animals exposed to FST and treated with mifepristone had significantly higher c-Fos activation in the anterior cingulate (A), prelimbic (B) and infralimbic (C) relative to all other groups. Data are represented as mean \pm S.E.M., $n = 6-10$ per group. Non-shared letters denote statistical significance, $p < 0.05$.

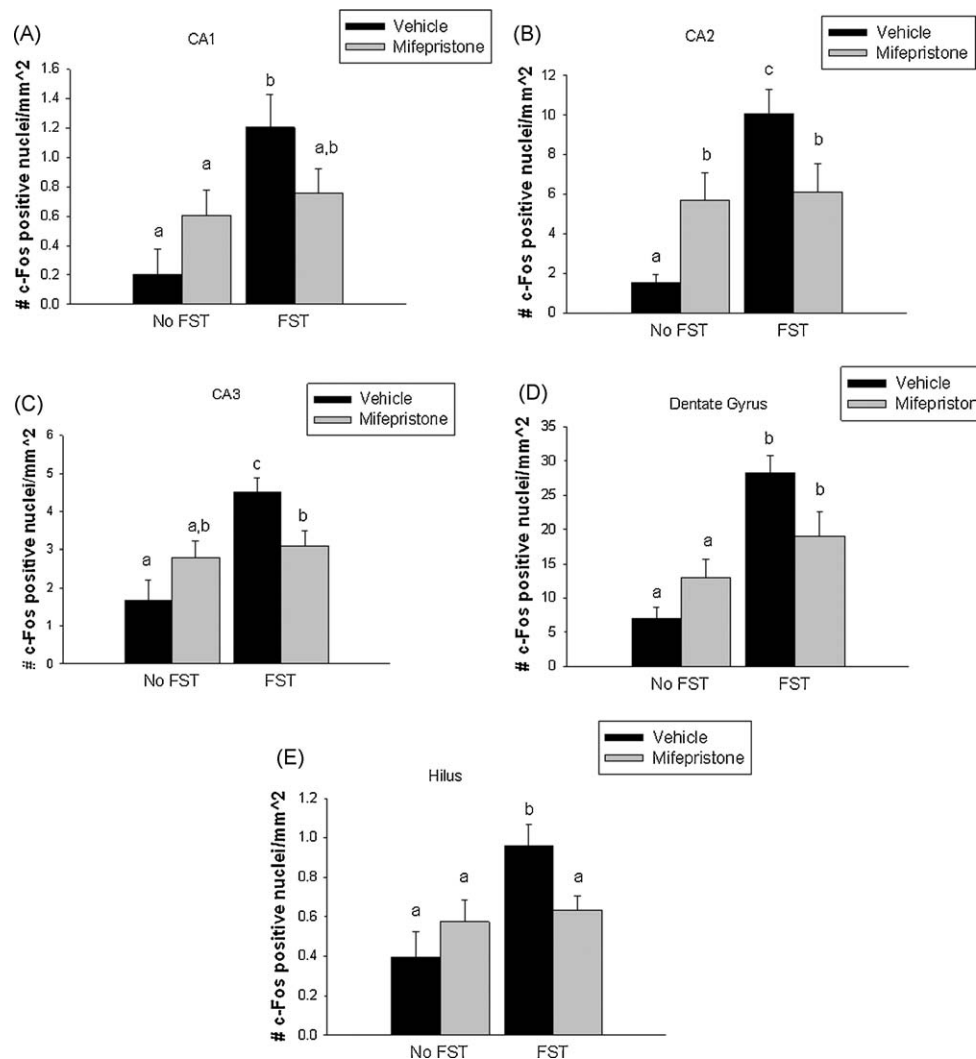


Figure 7 (A) Animals exposed to FST and treated with vehicle displayed greater c-Fos activation in the CA1 relative to the no FST group. (B) Vehicle treated animals exposed to FST displayed greater c-Fos activation relative to all other animals in the CA2. Within the CA2, mifepristone decreased c-Fos activation in animals exposed to FST relative to their FST-vehicle counterparts and the no FST-vehicle group. (C) Vehicle treated animals exposed to FST displayed greater c-Fos activation in the CA3 compared to all other groups. In particular, mifepristone decreased c-Fos activation in FST exposed animals compared with their FST-vehicle counterparts as well as the no FST-vehicle group. Data are represented as mean \pm S.E.M., $n = 6-10$ per group. Non-shared letters denote statistical significance, $p < 0.05$. (D) Animals exposed to FST displayed greater c-Fos activation in the dentate gyrus relative to non-stressed animals regardless of drug treatment. (E) Within the hilus area, animals exposed to FST and treated with vehicle displayed greater c-Fos activity relative to all other groups. Furthermore, animals exposed to FST and treated with mifepristone displayed decreased c-Fos activity relative to the vehicle treated animals. Data are represented as mean \pm S.E.M., $n = 6-10$ per group. Non-shared letters denote statistical significance, $p < 0.05$.

The FST-mifepristone group displayed less activity in the CeA relative to the FST vehicle treated group indicating that the drug dampened c-Fos activation in response to FST in this region (Fig. 10). In the basolateral amygdala, there was a significant main effect of stress ($F(1,31) = 24.06$, $p < 0.01$), no significant main effect of drug ($F(1,31) = .54$, $p > 0.05$) and no significant stress \times drug interaction ($F(1,31) = 1.10$, $p > 0.05$). Animals exposed to FST exhibited greater c-Fos activation in the BLA relative to non-stressed controls (Table 1). There was no main effect of stress, drug or significant stress \times drug interaction on c-Fos activation in the medial amygdala (Table 1).

3.4.5. Bed nucleus of stria terminalis

There was a significant main effect of stress on c-Fos expression in the anteroventral ($F(1,20) = 9.11$, $p < 0.01$) and lateral ($F(1,20) = 4.2$, $p = 0.05$) subdivisions of the BNST but no significant main effect of drug ($F(1,20) = .22$, $p > 0.05$) and no significant stress \times drug interaction ($F(1,20) = .01$, $p > 0.05$) (Table 1). In both cases, exposure to FST significantly increased c-Fos expression within the anteroventral and anterolateral subdivisions of the BNST compared with non-stressed controls. There was no significant main effect of stress or drug and no significant stress \times drug interaction on c-Fos expression in the posterior medial BNST (Table 1).

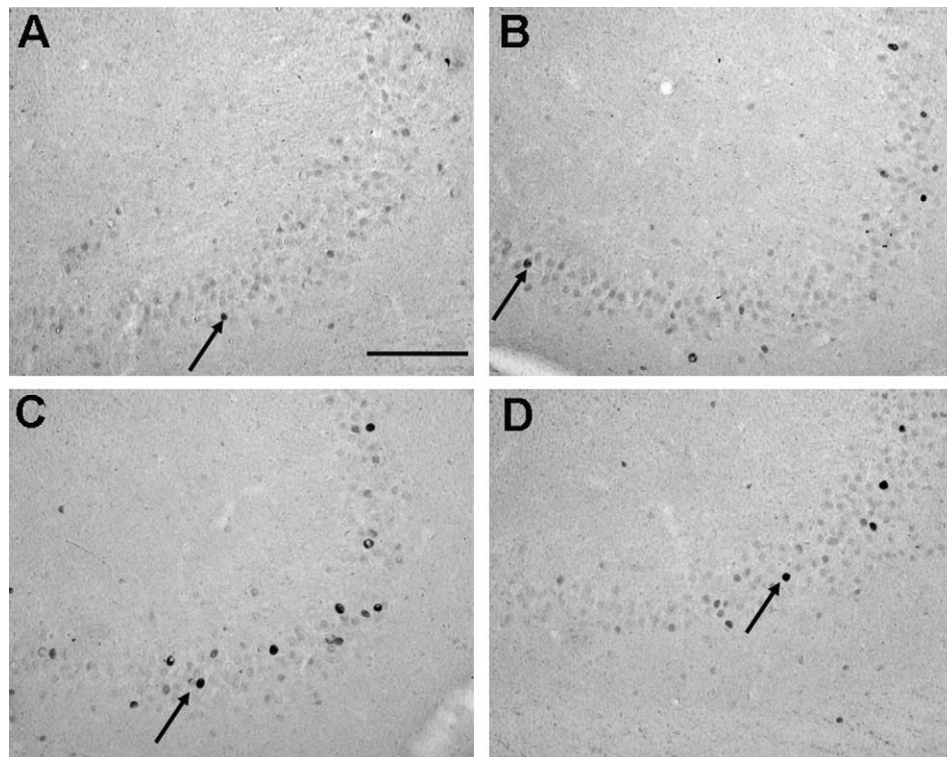


Figure 8 Representative image of c-Fos immunoreactivity in the CA3 region of the hippocampus at the level of -3.30 mm (bregma). (A) No FST vehicle, (B) No FST mifepristone, (C) FST vehicle and (D) FST mifepristone. Arrows indicate examples of c-Fos positive neurons. Immunohistochemistry results demonstrate that FST-mifepristone group displayed less neuronal activation within this region relative to the FST-vehicle group. Scale bar $100\ \mu\text{m}$.

3.4.6. Lateral septum

There was a significant main effect of stress on c-Fos expression in the ventral lateral septum ($F(1,34) = 6.11$, $p < 0.05$) but no significant main effect of drug or significant stress \times drug interaction. Animals exposed to FST exhibited significantly increased c-Fos expression within the ventral lateral septum compared with non-stressed controls (Table 1).

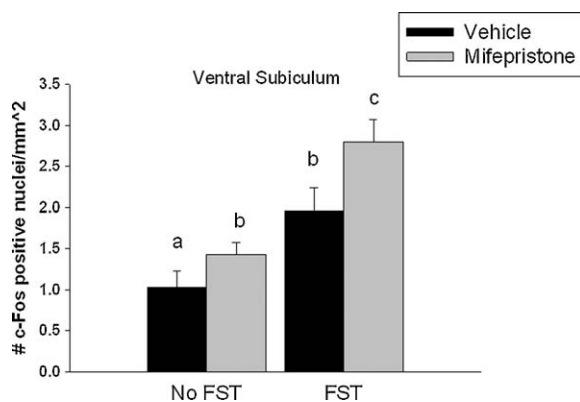


Figure 9 FST-mifepristone treated animals displayed greater c-Fos activation relative to all other groups within the ventral subiculum. Data are represented as mean \pm S.E.M., $n = 6-10$ per group. Non-shared letters denote statistical significance, $p < 0.05$.

3.4.7. Paraventricular nucleus of hypothalamus

There was a significant main effect of stress on c-Fos activation within the PVN ($F(1,30) = 103.08$, $p < 0.01$) but no significant main effect of drug and no significant stress \times drug interaction on c-Fos activation within this region. Animals exposed to FST exhibited greater c-Fos activation within the PVN relative to non-stressed controls (Table 1).

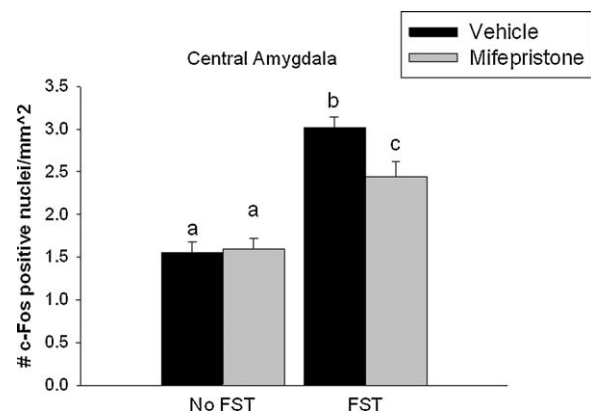


Figure 10 Animals exposed to FST and treated with vehicle displayed the greatest degree of c-Fos activation in the central amygdala relative to all other groups. The FST-mifepristone group displayed less c-Fos activation relative to the FST-vehicle treated group. Data are represented as mean \pm S.E.M., $n = 6-10$ per group. Non-shared letters denote statistical significance, $p < 0.05$.

Table 1 Effects of FST stress and drug treatment on Fos expression in male rats. Fos expression is corrected for area (mm²). φ indicates significant main effect of stress, $p < 0.05$.

	No FST		FST	
	Vehicle	Mifepristone	Vehicle	Mifepristone
<i>Amygdala</i>				
MeA	2.44 ± 0.40	1.81 ± 0.30	2.33 ± 0.21	1.97 ± 0.17
BLA φ	1.76 ± 0.11	2.23 ± 0.23	3.26 ± 0.22	3.42 ± 0.14
<i>Hypothalamus–thalamus</i>				
PVN φ	2.14 ± 0.15	2.24 ± 0.24	5.16 ± 0.36	5.50 ± 0.28
PVT φ	1.60 ± 0.36	2.00 ± 0.23	2.52 ± 0.19	2.85 ± 0.15
<i>BNST</i>				
Anteroventral φ	4.46 ± 0.55	3.25 ± 0.60	7.07 ± 0.98	6.34 ± 1.15
Ant. lateral φ	2.23 ± 0.39	2.01 ± 0.51	3.43 ± 0.53	3.14 ± 0.60
Post. medial	2.67 ± 0.64	2.52 ± 0.32	3.06 ± 0.28	2.82 ± 0.83
<i>Septal area</i>				
vLS φ	7.20 ± 1.54	5.81 ± 1.12	10.58 ± 1.40	11.87 ± 2.13

Abbreviations: MeA, medial amygdala; BLA, basolateral amygdala; PVN, paraventricular nucleus of the hypothalamus; PVT, paraventricular nucleus of the thalamus; BNST, bed nucleus of the stria terminalis; vLS, ventral lateral septum. Counts are reported in number of positive nuclei per unit area (mm²). Data are represented as mean ± S.E.M., $n = 8$ –10 per group (FST-mifepristone, FST-vehicle and No FST-mifepristone) and $n = 6$ per group (No FST-vehicle).

3.4.8. Paraventricular thalamic nucleus

There was a significant main effect of stress on c-Fos activation in the PVT ($F(1,30) = 14.24$, $p < 0.01$) but no significant main effect of drug and no significant stress \times drug interaction on c-Fos activation within this region. Animals exposed to FST exhibited greater c-Fos activation within the PVT relative to non-stressed controls (Table 1).

3.4.9. Terminal measures

There were no differences in body, adrenal, thymus and testes weights between animals treated with mifepristone and vehicle (data not shown), suggesting that 5 days of mifepristone were not sufficient to produce gross changes in reproductive and stress-responsive organs.

4. Discussion

The aim of the present study was to determine if the potential anti-depressant effects of mifepristone were due to modulation of neuroendocrine and central HPA axis responsiveness to stress. The results illustrate that repeated administration of mifepristone (5 days, 10 mg/kg) decreases immobility and increases swimming behavior in the modified FST, consistent with an anti-depressant effect. In addition, patterns of c-Fos induction in the CNS demonstrate that mifepristone induces an increase in neuronal activation in the medial prefrontal cortex and ventral subiculum and inactivation of the central amygdaloid nucleus, all of which are consistent with mifepristone-induced inhibition of central stress activation. Stress-dampening actions of mifepristone pretreatment are corroborated by decreased ACTH concentrations after FST exposure.

4.1. Modified forced swim test

In the present study, we utilized the modified version of the FST to assess depression-like behavior and neuroendocrine

and central responses to an acute stressor. The modified version of the FST used in this experiment obviates any potential confounds of learning and memory associated with the pretest in the traditional Porsolt FST and allows us to assess the rodent's reactivity to the novel stress environment. In Experiment 1, consistent with previous reports, imipramine was effective in decreasing immobility and increasing climbing and swimming behaviors (Barros and Ferigolo, 1998) indicative of an anti-depressant effect of a positive control compound in the modified FST. In Experiment 1, mifepristone was also effective in increasing swimming, but not climbing behaviors. Although there was a strong trend for decreased immobility in the mifepristone treated group versus those treated with vehicle, it did not reach significance. However, in Experiment 2, mifepristone decreased immobility and increased swimming behavior illustrating an anti-depressant-like effect of this compound. These findings are consistent with previous reports demonstrating decreased immobility in mifepristone treated animals in the traditional FST (de Kloet et al., 1988; Aisa et al., 2007, 2008). Of note, these studies only measured the impact of mifepristone on immobility; thus the effects of the compound on active behaviors were not discussed.

4.2. Neuroendocrine responses

Mifepristone decreased stress-induced ACTH and although not significantly, reduced corticosterone concentrations when compared to stressed animals treated with vehicle at the 15 min time-point. The lack of a significant effect of mifepristone on stress-induced corticosterone concentrations may be due to timing issues as peak corticosterone levels typically occur at later time-points (e.g., 30 min). The decreased stress-responsiveness with mifepristone treatment is consistent with a previous report by (Ratka et al., 1989) in which animals treated systemically with mifepristone prior to exposure to novel environment displayed

decreased stress-responsiveness (i.e., corticosterone) compared with vehicle treated animals. However, there are other reports whereby mifepristone increases neuroendocrine responsiveness to restraint stress in females prenatally exposed to ethanol (Glavas et al., 2006).

Our basal ACTH and corticosterone concentrations following mifepristone treatment are consistent with (de Kloet et al., 1988; Ratka et al., 1989; Spencer et al., 1998; Bachmann et al., 2003) which report no difference in tonic HPA axis activity with acute GR antagonism. On the other hand, others find increased basal ACTH and/or corticosterone concentrations following prolonged antagonism of GR with either mifepristone or selective GR antagonists (van Haarst et al., 1996; Bachmann et al., 2003). An increase in basal corticosterone following chronic treatment with mifepristone is not surprising since mifepristone acts by blocking GR which would increase the amount of freely circulating corticosterone. Belanoff and associates (2001) report that increased glucocorticoids following mifepristone treatment may be due to partial disruption of the GR mediated feedback. At the 90 min time-point, animals exposed to FST and treated with mifepristone had significantly higher corticosterone concentrations relative to all other groups, suggesting the possibility of a partial decrease in GR mediated feedback efficacy. These findings are also consistent with (Ratka et al., 1989) which report increased circulating corticosterone levels well after termination of novel environmental stress exposure (i.e., 240 min). Taken together, the present data suggest that mifepristone modulates the feed forward and the feedback components of the HPA axis specifically under periods of elevated glucocorticoids as seen during the FST.

4.3. c-Fos induction

4.3.1. Medial prefrontal cortex

Mifepristone increased activity in all regions of the mPFC. The rodent mPFC is divided into three main regions including the anterior cingulate, prelimbic (located in the dorsal mPFC) and the infralimbic (located in the ventral mPFC) cortices. Lesions studies in rats have demonstrated an inhibitory role of the anterior cingulate and prelimbic structures on HPA axis activation (Diorio et al., 1993; Figueiredo et al., 2003). In contrast, the infralimbic subdivision has an excitatory effect on HPA axis activation as bilateral lesions of this region decrease corticosterone response to restraint stress (Sullivan and Gratton, 1999). The infralimbic region in particular projects to many regions associated with HPA axis activation including the anterolateral BNST, CeA and the nucleus of the solitary tract, for review (Herman et al., 2003). The global increase in mPFC activation with mifepristone treatment is notable given that decreased activity in the mPFC is routinely observed in severely depressed patients (Drevets et al., 1997; Siegle et al., 2007).

4.3.2. Hippocampus

In the hippocampus, mifepristone had region specific effects in animals exposed to the FST, as neuronal activity was decreased in certain ventral regions of the hippocampus (CA2, CA3 and hilus) along with a trend for decreased activation in the CA1 region. In contrast, mifepristone increased neuronal activity within the ventral subiculum (the principle output region). The hippocampus is highly stress-responsive

and similar to the mPFC, contains an abundance of GR. Both clinical and preclinical data involving depressed individuals or chronic stress regimes demonstrates that the hippocampus undergoes marked alterations in volume size and synaptic plasticity (i.e., neurogenesis) presumably as a result of elevated glucocorticoids (Schmidt and Duman, 2007). The decrease in neuronal excitability within certain divisions of the hippocampus may serve as a protective mechanism to prevent the deleterious effects of glucocorticoids within this neural region. Consistent with this fact, mifepristone prevents stress-induced impairment in hippocampal LTP and corticosterone-induced decreases in hippocampal neurogenesis (Mayer et al., 2006; Mailliet et al., 2008). In contrast, mifepristone increased neuronal activity within the ventral subiculum in animals exposed to the FST. The ventral subiculum functions as the prime outflow area of the hippocampal formation (Herman and Mueller, 2006). Our laboratory has consistently demonstrated that the inhibitory effect of the hippocampus on HPA axis activity is via the ventral subiculum (Herman et al., 1995, 1998; Mueller et al., 2004). Therefore by increasing neuronal activity of this inhibitory output region, mifepristone may inhibit stressed-induced HPA axis outflow.

4.3.3. Amygdala

Mifepristone decreased neuronal activity in the CeA in animals exposed to the FST. Contrary to the inhibitory effects of the mPFC and hippocampus on HPA axis responses, the CeA has an excitatory effect as lesions to this region decrease neuroendocrine and central responses (c-fos) to a number of stressors (Beaulieu et al., 1986; Feldman et al., 1994; Xu et al., 1999). Consistent with its excitatory role in HPA axis activity, the CeA plays an integral role in the expression of fear responses. For example, lesions of the CeA blocks fear potentiated startle reflexes to either auditory or visual stimuli (Kim and Davis, 1993; Campeau and Davis, 1995). Together these findings suggest that the decreased neuronal activation in the CeA in animals exposed to FST and treated with mifepristone may underlie both the decreased neuroendocrine responses and decreased depression-like behavior.

4.3.4. Paraventricular nucleus of the hypothalamus

To our surprise, we did not find a significant difference in PVN activation in animals treated with mifepristone and exposed to the FST. The aforementioned regions do not project directly to the PVN but most likely via the BNST (Herman et al., 2003) an area in which we also did not see a mifepristone-mediated effect on stress responses. This suggests that mifepristone (at least within the context of the current study) dampens the neuroendocrine responses to stress in other areas outside of the PVN. The most likely target area outside of the PVN by which mifepristone modulates the neuroendocrine responses to stress is via direct action at the level of the anterior pituitary. The possibility that mifepristone modulates the neuroendocrine response to stress via interactions with the anterior pituitary is raised by (de Kloet et al., 1988). However, we did not assess c-Fos activation in the pituitary so we cannot definitely state whether this is indeed the case. We do want to emphasize that c-Fos expression in the aforementioned brain regions does not necessarily indicate that these are the only brain regions involved in depression and/or stress-related behaviors. For example,

there are many other regions that are involved in the stress-induced HPA axis activity and psychopathology and importantly, not all cells express c-Fos. It is also important to note that c-Fos activation may not be solely restricted to HPA axis function as other molecular mechanisms underlying mifepristone treatment may be associated with c-Fos expression.

We administered mifepristone for 5 days to be consistent with preclinical and clinical studies which reported protective effects against stress-induced decreases in neurogenesis (Flores et al., 2006; Mayer et al., 2006; Oomen et al., 2007; Mailliet et al., 2008) and therapeutic effects for the treatment of psychotic depression (Flores et al., 2006) with 4–8-day treatment. However, there are some shortcomings to this treatment regimen. First, prolonged antagonism of GR with mifepristone may permit glucocorticoids to signal through the mineralocorticoid receptor (MR) or the membrane-bound GR. Although MR is mainly viewed as being primarily important for regulating basal HPA axis activity, there are reports that MR is also important for stress-induced HPA axis activation (Pace and Spencer, 2005). Thus, we cannot completely rule out the role of MR or the membrane-bound GR on the behavioral, neuroendocrine or central stress responses in the present study. Second, it is difficult to discern whether the reported effects are due to acute or chronic effects of the drug because all of the animals were also injected 1 h prior to FST exposure. Finally, there may have been some adaptation due to repeated administration of the drug. The last point is less likely given that we see clear effects of the mifepristone only within the animals that are exposed to the FST.

4.3.5. Concluding remarks

Mifepristone decreased depression-like behavior and modulated the neuroendocrine and central stress responsiveness to the FST. As such, the cognitive appraisal of the FST may have been different in the animals treated with mifepristone versus vehicle. For example, animals treated with mifepristone may not have deemed the FST as “stressful” as those treated with vehicle. This difference in perception and behavior during FST exposure may subsequently alter both the neuroendocrine and central stress responsiveness and vice versa. However, this does not lessen the overall importance of the findings of the present study. The data demonstrate that mifepristone modifies central stress responsiveness in distinct neural regions that are associated with stress-responding and mood.

HPA axis dysregulation (i.e., hypercortisolemia) is often observed in depressed individuals but clinical depression is a complex psychopathology, likely due to several factors. Clearly, not all depressed individuals have alterations in HPA axis function; likewise, disturbances in HPA axis function do not necessarily lead to psychopathology. In fact, only a specific subpopulation of depressed individuals (psychotic depression) consistently demonstrate hypercortisolemia (DeBattista and Belanoff, 2006). Based on this knowledge, there are some limitations to the translation of the findings in the present study. For example, we examined the effect of mifepristone on HPA axis activation and mood in otherwise “normal” animals. However the present study was designed to determine if the reported anti-depressant effects of mifepristone were due to decreased neuroendocrine and central responses to stress. In this manner, the FST served as both the stressor as well as a tool to assess depression-like behavior. The modest effects of mifepristone on depression-like behavior in the modified

FST may be due to the fact that the drug appears to be particularly effective in alleviating depression-like behavior in individuals with elevated cortisol concentrations as seen in psychotic depressives (Belanoff et al., 2001; DeBattista and Belanoff, 2006; Flores et al., 2006). Consistent with this fact, the modulating effects of mifepristone on neuroendocrine and central stress responses were evident only during periods of elevated glucocorticoid secretion as seen with FST exposure. Therefore, studying the effects of the compound on the behavioral, neuroendocrine and central stress responses under regimens which induce both HPA axis hyperactivity and/or psychopathology are clearly warranted.

Role of funding sources

This work was supported by NIH MH 069725 to JPH and MBS and MH 49698 to JPH. NIH had no further role in the study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

Conflict of interest

None declared.

Acknowledgments

The authors would like to thank Benjamin Packard for assistance with radioimmunoassays and Kenneth Jones and Nathan Evanson, PhD for assistance with data imaging analysis. We would like to thank Ryan Jankord, PhD, Rong Zhang, PhD, Yve Ulrich-Lai, PhD, Jonathan Flak, Anne Christiansen and Annette Dekloet for helping with blood, organ and brain collection for this study.

References

- Aisa, B., Tordera, R., Lasheras, B., Del Rio, J., Ramirez, M.J., 2007. Cognitive impairment associated to HPA axis hyperactivity after maternal separation in rats. *Psychoneuroendocrinology* 32, 256–266.
- Aisa, B., Tordera, R., Lasheras, B., Del Rio, J., Ramirez, M.J., 2008. Effects of maternal separation on hypothalamic–pituitary–adrenal responses, cognition and vulnerability to stress in adult female rats. *Neuroscience* 154, 1218–1226.
- Arce, E., Simmons, A.N., Lovero, K.L., Stein, M.B., Paulus, M.P., 2008. Escitalopram effects on insula and amygdala BOLD activation during emotional processing. *Psychopharmacology (Berl.)* 196, 661–672.
- Bachmann, C.G., Linthorst, A.C., Holsboer, F., Reul, J.M., 2003. Effect of chronic administration of selective glucocorticoid receptor antagonists on the rat hypothalamic–pituitary–adrenocortical axis. *Neuropsychopharmacology* 28, 1056–1067.
- Bachmann, C.G., Bilang-Bleuel, A., De Carli, S., Linthorst, A.C., Reul, J.M., 2005. The selective glucocorticoid receptor antagonist ORG 34116 decreases immobility time in the forced swim test and affects cAMP-responsive element-binding protein phosphorylation in rat brain. *Neuroendocrinology* 81, 129–136.
- Barros, H.M., Ferigolo, M., 1998. Ethopharmacology of imipramine in the forced-swimming test: gender differences. *Neurosci. Biobehav. Rev.* 23, 279–286.
- Beaulieu, S., Di Paolo, T., Barden, N., 1986. Control of ACTH secretion by the central nucleus of the amygdala: implication of the

- serotonergic system and its relevance to the glucocorticoid delayed negative feedback mechanism. *Neuroendocrinology* 44, 247–254.
- Belanoff, J.K., Flores, B.H., Kalezhan, M., Sund, B., Schatzberg, A.F., 2001. Rapid reversal of psychotic depression using mifepristone. *J. Clin. Psychopharmacol.* 21, 516–521.
- Campeau, S., Davis, M., 1995. Involvement of the central nucleus and basolateral complex of the amygdala in fear conditioning measured with fear-potentiated startle in rats trained concurrently with auditory and visual conditioned stimuli. *J. Neurosci.* 15, 2301–2311.
- Cryan, J.F., Page, M.E., Lucki, I., 2005a. Differential behavioral effects of the antidepressants reboxetine, fluoxetine, and moclobemide in a modified forced swim test following chronic treatment. *Psychopharmacology (Berl.)* 182, 335–344.
- Cryan, J.F., Valentino, R.J., Lucki, I., 2005b. Assessing substrates underlying the behavioral effects of antidepressants using the modified rat forced swimming test. *Neurosci. Biobehav. Rev.* 29, 547–569.
- DeBattista, C., Belanoff, J., 2006. The use of mifepristone in the treatment of neuropsychiatric disorders. *Trends Endocrinol. Metab.* 17, 117–121.
- de Kloet, E.R., de Kock, S., Schild, V., Veldhuis, H.D., 1988. Anti-glucocorticoid RU 38486 attenuates retention of a behaviour and disinhibits the hypothalamic–pituitary–adrenal axis at different brain sites. *Neuroendocrinology* 47, 109–115.
- Delbende, C., Contesse, V., Mocaer, E., Kamoun, A., Vaudry, H., 1991. The novel antidepressant, tianeptine, reduces stress-evoked stimulation of the hypothalamo–pituitary–adrenal axis. *Eur. J. Pharmacol.* 202, 391–396.
- Diorio, D., Viau, V., Meaney, M.J., 1993. The role of the medial prefrontal cortex (cingulate gyrus) in the regulation of hypothalamic–pituitary–adrenal responses to stress. *J. Neurosci.* 13, 3839–3847.
- Drevets, W.C., Price, J.L., Simpson Jr., J.R., Todd, R.D., Reich, T., Vannier, M., Raichle, M.E., 1997. Subgenual prefrontal cortex abnormalities in mood disorders. *Nature* 386, 824–827.
- Feldman, S., Conforti, N., Itzik, A., Weidenfeld, J., 1994. Differential effect of amygdaloid lesions on CRF-41, ACTH and corticosterone responses following neural stimuli. *Brain Res.* 658, 21–26.
- Figueiredo, H.F., Bruestle, A., Bodie, B., Dolgas, C.M., Herman, J.P., 2003. The medial prefrontal cortex differentially regulates stress-induced c-fos expression in the forebrain depending on type of stressor. *Eur. J. Neurosci.* 18, 2357–2364.
- Flores, B.H., Kenna, H., Keller, J., Solvason, H.B., Schatzberg, A.F., 2006. Clinical and biological effects of mifepristone treatment for psychotic depression. *Neuropsychopharmacology* 31, 628–636.
- Glavas, M.M., Yu, W.K., Weinberg, J., 2006. Effects of mineralocorticoid and glucocorticoid receptor blockade on hypothalamic–pituitary–adrenal function in female rats prenatally exposed to ethanol. *Alcohol Clin. Exp. Res.* 30, 1916–1924.
- Gold, P.W., Chrousos, G.P., 1999. The endocrinology of melancholic and atypical depression: relation to neurocircuitry and somatic consequences. *Proc. Assoc. Am. Physicians* 111, 22–34.
- Herman, J.P., Mueller, N.K., 2006. Role of the ventral subiculum in stress integration. *Behav. Brain Res.* 174, 215–224.
- Herman, J.P., Dolgas, C.M., Carlson, S.L., 1998. Ventral subiculum regulates hypothalamo–pituitary–adrenocortical and behavioural responses to cognitive stressors. *Neuroscience* 86, 449–459.
- Herman, J.P., Cullinan, W.E., Morano, M.I., Akil, H., Watson, S.J., 1995. Contribution of the ventral subiculum to inhibitory regulation of the hypothalamo–pituitary–adrenocortical axis. *J. Neuroendocrinol.* 7, 475–482.
- Herman, J.P., Figueiredo, H., Mueller, N.K., Ulrich-Lai, Y., Ostrander, M.M., Choi, D.C., Cullinan, W.E., 2003. Central mechanisms of stress integration: hierarchical circuitry controlling hypothalamo–pituitary–adrenocortical responsiveness. *Front. Neuroendocrinol.* 24, 151–180.
- Ishizaki, J., Yamamoto, H., Takahashi, T., Takeda, M., Yano, M., Mimura, M., 2008. Changes in regional cerebral blood flow following antidepressant treatment in late-life depression. *Int. J. Geriatr. Psychiatry* 23, 805–811.
- Jasper, M.S., Engeland, W.C., 1991. Synchronous ultradian rhythms in adrenocortical secretion detected by microdialysis in awake rats. *Am. J. Physiol.* 261, R1257–1268.
- Kim, M., Davis, M., 1993. Electrolytic lesions of the amygdala block acquisition and expression of fear-potentiated startle even with extensive training but do not prevent reacquisition. *Behav. Neurosci.* 107, 580–595.
- Kukolja, J., Schlapfer, T.E., Keyser, C., Klingmüller, D., Maier, W., Fink, G.R., Hurlmann, R., 2008. Modeling a negative response bias in the human amygdala by noradrenergic–glucocorticoid interactions. *J. Neurosci.* 28, 12868–12876.
- Mailliet, F., Qi, H., Rocher, C., Spedding, M., Svenningsson, P., Jay, T.M., 2008. Protection of stress-induced impairment of hippocampal/prefrontal LTP through blockade of glucocorticoid receptors: implication of MEK signaling. *Exp. Neurol.* 211, 593–596.
- Mayer, J.L., Klumpers, L., Maslam, S., de Kloet, E.R., Joels, M., Lucassen, P.J., 2006. Brief treatment with the glucocorticoid receptor antagonist mifepristone normalises the corticosterone-induced reduction of adult hippocampal neurogenesis. *J. Neuroendocrinol.* 18, 629–631.
- Morley-Fletcher, S., Darnaudery, M., Mocaer, E., Froger, N., Lanfumey, L., Laviola, G., Casolini, P., Zúena, A.R., Marzano, L., Hamon, M., Maccari, S., 2004. Chronic treatment with imipramine reverses immobility behaviour, hippocampal corticosteroid receptors and cortical 5-HT(1A) receptor mRNA in prenatally stressed rats. *Neuropharmacology* 47, 841–847.
- Mueller, N.K., Dolgas, C.M., Herman, J.P., 2004. Stressor-selective role of the ventral subiculum in regulation of neuroendocrine stress responses. *Endocrinology* 145, 3763–3768.
- Oomen, C.A., Mayer, J.L., de Kloet, E.R., Joels, M., Lucassen, P.J., 2007. Brief treatment with the glucocorticoid receptor antagonist mifepristone normalizes the reduction in neurogenesis after chronic stress. *Eur. J. Neurosci.* 26, 3395–3401.
- Pace, T.W., Spencer, R.L., 2005. Disruption of mineralocorticoid receptor function increases corticosterone responding to a mild, but not moderate, psychological stressor. *Am. J. Physiol. Endocrinol. Metab.* 288, E1082–E1088.
- Pariante, C.M., 2003. Depression, stress and the adrenal axis. *J. Neuroendocrinol.* 15, 811–812.
- Paxinos, G., Watson, C., 1998. *The Rat Brain in Stereotaxic Coordinates*, 4th ed. Academic Press, Inc., California, p. 474.
- Porsolt, R.D., Le Pichon, M., Jalfre, M., 1977. Depression: a new animal model sensitive to antidepressant treatments. *Nature* 266, 730–732.
- Ratka, A., Sutanto, W., Bloemers, M., de Kloet, E.R., 1989. On the role of brain mineralocorticoid (type I) and glucocorticoid (type II) receptors in neuroendocrine regulation. *Neuroendocrinology* 50, 117–123.
- Reul, J.M., Labeur, M.S., Grigoriadis, D.E., De Souza, E.B., Holsboer, F., 1994. Hypothalamic–pituitary–adrenocortical axis changes in the rat after long-term treatment with the reversible monoamine oxidase-A inhibitor moclobemide. *Neuroendocrinology* 60, 509–519.
- Schmidt, H.D., Duman, R.S., 2007. The role of neurotrophic factors in adult hippocampal neurogenesis, antidepressant treatments and animal models of depressive-like behavior. *Behav. Pharmacol.* 18, 391–418.
- Siegle, G.J., Thompson, W., Carter, C.S., Steinhauer, S.R., Thase, M.E., 2007. Increased amygdala and decreased dorsolateral prefrontal BOLD responses in unipolar depression: related and independent features. *Biol. Psychiatry* 61, 198–209.
- Spencer, R.L., Kim, P.J., Kalman, B.A., Cole, M.A., 1998. Evidence for mineralocorticoid receptor facilitation of glucocorticoid recep-

- tor-dependent regulation of hypothalamic–pituitary–adrenal axis activity. *Endocrinology* 139, 2718–2726.
- Sullivan, R.M., Gratton, A., 1999. Lateralized effects of medial prefrontal cortex lesions on neuroendocrine and autonomic stress responses in rats. *J. Neurosci.* 19, 2834–2840.
- Thomson, F., Craighead, M., 2008. Innovative approaches for the treatment of depression: targeting the HPA axis. *Neurochem. Res.* 33, 691–707.
- van Haast, A.D., Oitzl, M.S., Workel, J.O., de Kloet, E.R., 1996. Chronic brain glucocorticoid receptor blockade enhances the rise in circadian and stress-induced pituitary–adrenal activity. *Endocrinology* 137, 4935–4943.
- Xu, Y., Day, T.A., Buller, K.M., 1999. The central amygdala modulates hypothalamic–pituitary–adrenal axis responses to systemic interleukin-1beta administration. *Neuroscience* 94, 175–183.