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Dysregulation of Diurnal Rhythms of Serotonin 5-HT2C and Corticosteroid Receptor Gene Expression in the Hippocampus with Food Restriction and Glucocorticoids

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Abnormalities of both serotonergic (5-HT) and hypothalamic-pituitary-adrenal (HPA) axis activity are found in depression and eating disorders and may play important pathogenic roles. Both conditions are frequently associated with elevated plasma cortisol levels (Carroll et al., 1976) and insensitivity to glucocorticoid (dexamethasone) feedback (Carroll, 1982), presumed to be caused by increased central drive on the HPA axis. Abnormal 5-HT neurotransmission is also believed to be a key factor in depression (Meltzer and Lowy, 1987). Many clinically efficacious antidepressants alter 5-HT neurotransmission, improving both mood and hypercortisolemia (Ogren et al., 1979; Linkowski et al., 1987).

Glucocorticoids act via intracellular high-affinity mineralocorticoid receptors (MRs) and lower-affinity glucocorticoid receptors (GRs) (Reul and de Kloet, 1985; McEwen et al., 1986). In contrast, 5-HT binds to a number of distinct cell membrane sites (Peroutka, 1993). The hippocampus has a dense 5-HT innervation, highly expresses both corticosteroid and 5-HT receptors (Palacios et al., 1990; de Kloet, 1991; Wright et al., 1995), and is an important locus for the interaction of the two systems. Serotonin is important for the maintenance of corticosteroid receptor gene expression in the hippocampus (Seckl et al., 1990; Yau et al., 1994). Similarly, glucocorticoids alter hippocampal expression of at least two 5-HT receptor subtypes, 5-HT1A (Chalmers et al., 1993; Zhong and Ciaranello, 1995) and 5-HT2C (Holmes et al., 1995), 5-HT1A and 5-HT2C receptors are excellent candidates to mediate functional abnormalities in depression and both are highly expressed in the hippocampus (Mengod et al., 1990; Chalmers and Watson, 1991). Sets of antidepressant drugs act on each receptor (Robinson, 1993), and both are implicated in HPA regulation (Fuller, 1992). m-Chlorophenylpiperazine (mCPP), which binds to 5-HT2C receptors with high affinity, increases plasma glucocorticoid levels, reduces food intake (Blundell, 1992; Clifton et al., 1993), attenuates locomotion, and exerts dysphoric effects in some depressive illnesses (JosephVanderpool et al., 1993; Jacobsen et al., 1994), whereas 5-HT2C (and -2A) receptor antagonists (e.g., ketanserin and ritanserin) are clinically efficacious antidepressants (Robinson, 1993).

The mRNAs encoding 5-HT2C receptors, GR, and MR, but not 5-HT1A receptors, exhibit a circadian rhythm in the hippocampus (Herman et al., 1993; Holmes et al., 1995a,b). Affective disorders are frequently associated with blunting (elevation) of the normal afternoon/evening nadir of the cortisol circadian rhythm (Linkowski et al., 1987). Central 5-HT activity also shows a diurnal rhythm, with higher 5-HT release in the hippocampus during the active period (darkness in rats) (Kalén et al., 1989). Other

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diurnal functions (e.g., sleep, psychological performance) are also disrupted in depression (Healy, 1987), and clearly, diurnally varying processes underlying the interaction between 5-HT and cortisol may be important to understanding abnormal central mechanisms in affective disorders (Moffitt et al., 1994). In previous work we found that the rhythm of hippocampal 5-HT_{2C} receptor gene expression was maintained in adrenalectomized rats (Holmes et al., 1995b) but suppressed by chronic stress-mediated elevations of plasma corticosterone (Holmes et al., 1995a), presumably an adaptive process to attenuate sensitivity of this receptor with chronic stress. To investigate further the diurnal cues regulating hippocampal receptor expression, a food restriction paradigm (Krieger and Hauser, 1978) was used that alters the plasma corticosterone rhythm as well as feeding and locomotor behavior, leaving only the light–dark cues unchanged.

In this study we wished to determine (1) the control of corticosteroid and serotonin receptor mRNA expression in the hippocampus throughout the 24 hr period, (2) any link between diurnal hippocampal 5-HT_{2C} receptor mRNA changes and possible diurnal rhythms in 5-HT_{2C} receptor-mediated behaviors, and (3) the role of diurnal glucocorticoid effects and food restriction (a chronic intermittent and perhaps pathophysiologically relevant stressor) on the diurnal patterns of receptor gene expression.

MATERIALS AND METHODS

Behavioral experiments

Open field behavior in response to mCPP. Male Han–Wistar rats were given mCPP (1 mg/kg, i.p.; Sigma, St, Louis, MO) or saline 30 min before testing in the open field (novel environment). Animals were placed in a large Perspex box ([60 × 40 cm]) divided into eight zones for 5 min. The number of times the rat crossed into a new zone and the number of rearings were recorded. Animals (six to eight per group) were tested at 9 A.M., 1 P.M., or 5 P.M.

Inhibition of food intake in response to mCPP. Sixteen rats (~300 gm) were housed singly in a light-controlled environment (lights on from 7 A.M. to 7 P.M.). To test the feeding response to the 5-HT_{2C} receptor agonist, animals were fasted overnight, and then 30 min after an intraperitoneal injection of saline or mCPP (1 mg/kg), the amount of food ingested over a 1 hr period was determined. mCPP or saline were given in a random design, spaced 1 week apart at 9 A.M. and 1, 5, and 9 P.M.

Food restriction

Han–Wistar rats (~250 gm) were housed in pairs and handled daily for 1 week before the study. Lights were on from 7 A.M. to 7 P.M. For food restriction studies, rats were allowed access to food pellets only between 10 A.M. and noon. Water was available ad libitum. The animals were entrained to the food restriction regimen for 3 weeks before they were killed. Controls had tap water and rat chow available 24 hr a day, midnight). Care was taken to cause minimal stress to the rats before decapitation, which was completed within 1 min of disturbing a cage.

In situ hybridization histochemistry.

In situ hybridization histochemistry was performed as described previously (Seckl et al., 1990; Yau et al., 1994). In brief, sections were post-fixed in 4% paraformaldehyde and washed in 2× SSC. For 5-HT receptor subtype mRNA detection, sections were prehybridized with hybridization buffer at 50°C. After hybridization, sections for GR and MR RNA detection were hybridized directly. [35S]UTP-labeled mRNA antisense probes were transcribed in vitro from linearized plasmids of rat 5-HT_{1A} receptor cDNA (Albert et al., 1990) and 5-HT_{2C} receptor cDNA (Julius et al., 1988), GR, and MR cDNA as described previously (Seckl et al., 1990). Probes (10–20 × 10^6 counts/ml) were denatured, added to hybridization buffer, applied to sections, hybridized, and washed under stringent conditions, as reported previously (Seckl et al., 1990). Slides were dipped in Kodak NTB2 emulsion, exposed at 4°C for 4 weeks, developed, and counterstained (1% pyronin). Expression was quantified by counting silver grains overlying identified neurons under bright-field illumination using a computer-driven image analysis system (Seescan, Cambridge, UK) and ratio-of-change filters (Alldridge and Seckl, 1993). Expression was estimated over at least 15 cells per subfield for each animal. Specificity was demonstrated using 35S-labeled “sense” RNA probes of similar specific activity, hybridized under identical conditions. No specific cellular hybridization signal was seen with any sense probe (data not shown; but see Seckl et al., 1990).

Plasma corticosterone measurements

Corticosterone was measured in trunk blood samples by specific radioimmunoassay, as described previously (MacPhee et al., 1989) with anti-serum donated by Dr. C. Kenyon, Edinburgh. The detection limit of the assay was 6 nmol/l.

Statistical analysis

For the in situ hybridization results, the average number of grains counted over each hippocampal area was standardized for each experiment as percentage grains of the 8 P.M. control group (n = 4–6 per group). All results were analyzed by one- or two-way ANOVA, followed by Dunnett’s post hoc test. Significance levels were taken as p < 0.05. For the mCPP-induced effects, the drug group was compared with the control group at each time of day using a t test (n = 6–8).

RESULTS

Circadian rhythm of hippocampal 5-HT_{2C} receptor mRNA expression and 5-HT_{2C} receptor agonist-induced behavior

A diurnal rhythm of 5-HT_{2C} receptor mRNA expression was seen in the ventral CA1 region of the hippocampus (Fig. 1A) as well as dorsal CA1 and subiculum. When 5-HT_{2C} receptor agonist-induced behavior was compared at different times of day, a diurnal rhythm in agonist effectiveness was apparent (Fig. 1B,C). In the open field test, mCPP significantly inhibited the locomotor activity of the rats, as determined by the number of crossings of the open field zones, at 9 A.M. but not at 1 or 5 P.M. (Fig. 1B). Similarly, the number of rearings was significantly reduced in the

were allowed to recover from anesthesia and placed in cages in pairs (with 0.9% saline to drink for the adrenalectomized rats) for 7 d before they were killed at either 8 A.M. or 8 P.M. Groups contained five to six animals.

Adrenalectomy and pulsatile corticosterone replacement

To determine whether the timing of the corticosterone peak was important in the regulation of hippocampal receptor gene expression, rats were adrenalectomized and given corticosterone injections (20 mg/kg, s.c., in 200 μl of corn oil for 7 d) at various times of day. One group received corticosterone injections at 8 A.M., the normal diurnal nadir of corticosterone. Another group received corticosterone at 6 P.M. to reproduce the normal elevation of plasma corticosterone levels at the onset of the dark phase. Controls were sham adrenalectomized and received 200 μl of corn oil daily. Rats (four per group) were killed at 8–10 A.M., 2–4 P.M., and 8–10 P.M.; the brains were removed and processed for in situ hybridization histochemistry, as above.

5-HT and GR subtype in situ hybridization histochemistry

In situ hybridization histochemistry was performed as described previously (Seckl et al., 1990; Yau et al., 1994). In brief, sections were post-fixed in 4% paraformaldehyde and washed in 2× SSC. For 5-HT receptor subtype mRNA detection, sections were prehybridized with hybridization buffer at 50°C. After hybridization, sections for GR and MR RNA detection were hybridized directly. [35S]UTP-labeled mRNA antisense probes were transcribed in vitro from linearized plasmids of rat 5-HT_{1A} receptor cDNA (Albert et al., 1990) and 5-HT_{2C} receptor cDNA (Julius et al., 1988), GR, and MR cDNA as described previously (Seckl et al., 1990). Probes (10–20 × 10^6 counts/ml) were denatured, added to hybridization buffer, applied to sections, hybridized, and washed under stringent conditions, as reported previously (Seckl et al., 1990). Slides were dipped in Kodak NTB2 emulsion, exposed at 4°C for 4 weeks, developed, and counterstained (1% pyronin). Expression was quantified by counting silver grains overlying identified neurons under bright-field illumination using a computer-driven image analysis system (Seescan, Cambridge, UK) and ratio-of-change filters (Alldridge and Seckl, 1993). Expression was estimated over at least 15 cells per subfield for each animal. Specificity was demonstrated using 35S-labeled “sense” RNA probes of similar specific activity, hybridized under identical conditions. No specific cellular hybridization signal was seen with any sense probe (data not shown; but see Seckl et al., 1990).

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mCPP-treated animals at 9 A.M. and 1 P.M., but not at 5 P.M. (Fig. 1C); however, there was no effect of time of day on the efficacy of mCPP to inhibit feeding (Fig. 1D).

Figure 1. Diurnal variation of 5-HT\textsubscript{2c} receptor mRNA expression and mCPP-induced behaviors. A, 5-HT\textsubscript{2c} receptor mRNA expression in the CA1 subregion of the hippocampus over a 24 hr period. Receptor mRNA levels were determined by \textit{in situ} hybridization histochemistry. The mean number of grains/subregion/rat was standardized to the expression observed in the control rats at 8 P.M. (20) (100%). Values represent mean ± SEM; n = 4. *p < 0.05 compared with 8 A.M. (8). B–D, Sensitivity to mCPP-induced inhibition; B, locomotor behavior; C, rearings in an open field. The % number of crossings of open field zones and % number of rearings in a 5 min period after mCPP (1 mg/kg, i.p.) 30 min before testing, compared with controls (saline injected) tested at the same time of day. Numbers per group = 6–8. D, The % inhibition of food intake 30 min after mCPP (1 mg/kg, i.p.) compared with control animals tested at the same time of day. Animals were fasted overnight before testing, and the test period was for 1 hr. Numbers of animals per group = 8. All columns represent mean results per group ±SEM. *p < 0.05 compared with controls tested at the same time of day. Time of day: 9 = 9 A.M.; 13 = 1 P.M.; 17 = 5 P.M.; 21 = 9 P.M.

Figure 2. Twenty-four hour profile of plasma corticosterone (Plasma B) levels in control (●) and in animals after 3 week food restriction (□). Values represent mean ± SEM; n = 4–8. □ represents period of food availability for food-restricted animals, and black bars represent period of darkness. Time notation as in Figure 1 legend.

The effect of food restriction on plasma corticosterone and hippocampal receptor gene expression

Body weight and food intake

During the 3 week period of the food restriction experiment, the control rats increased their weight by 16%, whereas the animals fed for only 2 hr/d maintained their initial body weight. The food intake per day was 14 ± 1 gm for the animals on food restriction compared with 22 ± 1 gm for the control rats fed \textit{ad libitum}.

Plasma corticosterone

In control animals, plasma corticosterone showed a well defined diurnal rhythm, with a nadir at 8 A.M.–noon and a peak at 8 P.M. (Fig. 2). Chronic exposure to food restriction (food available only from 10 A.M.–noon) produced a biphasic rhythm in plasma corticosterone, with a novel peak at 8 A.M. (just before food availability) as well as the usual diurnal peak at 8 P.M. (just after lights off and at the beginning of the activity period). Food-restricted rats, however, showed a plasma corticosterone nadir, although delayed, at 4 P.M. (Fig. 2). The total 24 hr secretion of corticosterone in food-restricted rats was significantly greater (94% higher) than in controls with access to food \textit{ad libitum}.

5-HT\textsubscript{2c} receptor mRNA expression

5-HT\textsubscript{2c} receptor mRNA expression, measured in various subregions of the hippocampus at 4 hr intervals, exhibited a monophasic rhythm in dorsal CA1, ventral CA1, and subiculum, peaking at 4–8 A.M. and falling to a nadir at 8 P.M. (Fig. 3A). The rhythm in receptor expression is similar to the rhythm in plasma corticosterone; however, it is shifted to the right (delayed) by 4–8 hr. In contrast to plasma corticosterone, the rhythm in 5-HT\textsubscript{2c} receptor gene expression in dorsal CA1, ventral CA1, and subiculum were unaltered in food-restricted animals (Fig. 3A). No circadian changes were seen in 5-HT\textsubscript{2c} receptor mRNA expression in CA3 in either group (data not shown).

5-HT\textsubscript{1A} receptor mRNA expression

No changes in 5-HT\textsubscript{1A} receptor mRNA expression were observed over the 24 hr period in any region of the hippocampus measured (Fig. 3B). Furthermore, food restriction exerted no effect on
5-HT_{1A} receptor mRNA expression in the hippocampus (DG, CA1, and subiculum) at any time of day (Fig. 3B).

**MR mRNA expression**

In control rats, hippocampal MR gene expression exhibited a clear significant circadian rhythm, with a peak at 8 A.M. and a nadir between midnight and 4 A.M., in both dentate gyrus and CA1 neurons (Fig. 4A). No diurnal variation in MR mRNA was found in CA3. After food restriction the rhythm of MR gene expression was disrupted with a nonsignificant variance with time. Within this, the peak MR mRNA expression was delayed until 4 P.M., although the nadir remained at midnight.

**GR mRNA expression**

There was also a clear significant diurnal rhythm of GR mRNA expression in controls, again confined to the dentate gyrus and CA1. The diurnal peak was at 8 A.M. and the nadir at midnight (Fig. 4B). Food restriction altered the rhythms of GR mRNA in both dentate gyrus and CA1, although significant variance with respect to time of day persisted. In the dentate gyrus, the GR mRNA peak shifted to 8 P.M., whereas in CA1 peaks at noon and 8 P.M. occurred (Fig. 4B), a biphasic pattern similar to plasma corticosterone levels (correlation of GR mRNA changes with plasma B changes; \( p = 0.03 \)). No significant changes in GR gene expression were observed over time in the CA3 region of the hippocampus in either group.

**The effect of constant corticosterone levels on circadian variations in hippocampal receptor gene expression**

In rats sham-adrenalectomized with placebo pellet, plasma corticosterone levels showed a normal circadian variation (low morning and high evening levels) (Fig. 5). Adrenalectomized rats with 100 mg corticosterone pellets had plasma corticosterone levels modestly elevated over the control morning nadir but fixed throughout the day (Fig. 5). Sham-adrenalectomized controls had higher hippocampal 5-HT_{2C} receptor mRNA expression at 8 A.M. than at 8 P.M. (Fig. 6a), as seen in the (unoperated) controls in the first study; however, constant corticosterone levels abolished the diurnal rhythm. Expression was fixed at levels similar to the 5-HT_{2C} receptor mRNA nadir at 8 P.M., most notably in ventral CA1 and the subiculum. Similarly, the normal diurnal variation in MR and GR gene expression in the hippocampus was lost in animals with constant corticosterone levels (Fig. 6c,d). GR

![Figure 3](image-url)
mRNA levels approximated the evening diurnal nadir with constant corticosterone, whereas MR mRNA expression was not clearly repressed, although diurnal variation was absent. No differences were observed in 5-HT1A receptor mRNA expression in the hippocampus of any group (Fig. 6).

The effect of pulsatile corticosterone on hippocampal 5-HT2C receptor mRNA expression

To examine the possibility that the absence of a double diurnal peak in hippocampal 5-HT2C receptor gene expression in parallel to plasma corticosterone in food-restricted rats might reflect anergy of the response to elevated glucocorticoids in the morning, corticosterone was administered by injection in the morning and at the normal diurnal peak (evening). Injection of corticosterone produced elevated plasma corticosterone for 12 hr (Fig. 7). Corticosterone injection at 8 A.M. resulted in a constant level of 5-HT2C receptor gene expression throughout the day in all hippocampal subfields (CA1 data shown in Fig. 7B). In contrast, injection of corticosterone at 6 P.M., just before lights off, produced a rise in 5-HT2C receptor mRNA expression in CA1 (Fig. 7C) and subiculum (not shown) at 8 A.M., similar to that in sham-adrenalectomized (Fig. 7A) and other control animals.

Variations of 5-HT2C receptor mRNA expression at extra-hippocampal sites

To determine whether the circadian variation is specific to the hippocampus, 5-HT2C receptor gene expression was also determined in other areas of the brain. 5-HT2C receptor mRNA expression was measured at 8 A.M. and 8 P.M. in the suprachiasmatic nucleus (SCN), preoptic area, bed nucleus of the stria terminalis (BNST), retrosplenial granule cortex, paraventricular nucleus of the hypothalamus (PVN), ventromedial nucleus, dorsomedial nucleus, lateral hypothalamus, and amygdala. Most areas did not show any variation of expression with time of day. The two exceptions were the BNST, which like the hippocampus had higher 5-HT2C receptor gene expression at 8 A.M., and the PVN, which had an opposite rhythm, showing higher expression at 8 P.M. (Fig. 8).

Figure 4. Twenty-four hour profile of (A) MR and (B) GR mRNA expression in control (■) and food-restricted (△) animals in various hippocampal subregions. Receptor mRNA levels were determined by in situ hybridization histochemistry. The mean number of grains/subregion/rat was standardized to the expression observed in the control rats at 8 P.M. (20) (100%). Values represent mean ± SEM; n = 4. *p < 0.05 compared with peak value. Time notation as in Figure 1 legend.
subcutaneously (rats adrenalectomized with a 100 mg corticosterone slow-release pellet hence 5-HT2C receptor-mediated behaviors. The number of binding sites available and hence 5-HT2C receptor-sion is translated into a rhythm of 5-HT 2C receptor protein and a clear monophasic diurnal rhythm of 5-HT2C receptor gene of the hippocampus in the morning (Holmes et al., 1995a) to show on the diurnal rhythm of plasma corticosterone. In this study, have shown previously that food restriction has a potent influence rise at the beginning of the dark phase. Krieger and Hauser (1978) Chronic food restriction altered the normal diurnal profile of the glucocorticoid rhythm, possibly associated with the light–dark cycle cues. 5-HT2C receptor mRNA, however, is suppressed in the hippocampus by continuously elevated glucocorticoids [at diurnal maximum levels (Donaldson et al., 1993)] in chronic arthritis stress (Holmes et al., 1995a). This suppression is also seen with continuously but very modestly elevated corticosterone levels using low-dose pellets in this study, suggesting that whenever glucocorticoids are persistently elevated above low basal levels they suppress the rhythm of hippocampal 5-HT2C receptor mRNA (a summary of the correlation of 5-HT2C receptor mRNA expression in the hippocampus with plasma corticosterone profiles is presented in Fig. 9).

These effects of glucocorticoids, however, are clearly dependent on the manner and timing of exposure. When corticosterone levels were increased during the dark phase (mimicking the normal circadian rhythm), a normal rhythm in 5-HT2C receptor mRNA was observed. This rhythm was abolished, with suppressed receptor gene expression, if the same dose of corticosterone was given with a peak in the daylight hours. These data suggest that a nadir of corticosterone coinciding with the light-phase period of inactivity is required for the normal nocturnal increase in hippocampal 5-HT2C receptor mRNA expression. This contention is supported by the effects of food restriction. This procedure did not suppress the rhythm of 5-HT2C receptor mRNA expression in the hippocampus, despite markedly elevated mean plasma corticosterone levels. There was a clear diurnal nadir of corticosterone (~100 nmol/l) during the day, however, which thus may allow the later rise of 5-HT2C receptor transcripts. Of course, providing the mRNA is translated (data from the behavioral studies suggest that this hypothesis is likely), then food restriction may inappropriately maintain 5-HT2C receptor sensitivity in the face of chronic intermittent stress and increased 5-HT transmission, perhaps amplifying the deleterious actions on mood and behavior mediated by this receptor subtype (Kennett et al., 1989, 1994). In contrast, continuously elevated glucocorticoids or loss of the association between the light–dark cycle and corticosterone suppresses the 5-HT2C receptor rhythm and therefore presumably reduces the overall sensitivity to activation of 5-HT2C receptors. Perhaps much greater levels of stress or glucocorticoids are required under such circumstances to overcome the “compensatory” decrease in receptor expression before adverse affective events may occur. The food restriction protocol thus may be useful to investigate intermittent stress or mismatch effects, perhaps as occur in depression and eating disorders (Fig. 9).

The implications of the different effects of chronic intermittent versus continuous glucocorticoid excess (i.e., stress vs Cushing’s
disease or pharmacotherapy) on mood pathology remain to be explored; however, increased 5-HT$_{2C}$ binding sites occur in animals exposed to chronic unpredictable stress (an animal model of depression) when plasma corticosterone levels are allowed to reach nadir levels between stresses (Moreau et al., 1993). Furthermore, animals reared in isolation have increased sensitivity to 5-HT$_{2C}$ agonists (Fone et al., 1996), confirming in another model of depression the importance of 5-HT$_{2C}$ receptor sensitivity. Patients with depression exhibit abnormal circadian rhythms of plasma cortisol, with a prolonged peak and early timing of the nadir, although a transient (or elevated) nadir usually occurs (Linkowski et al., 1987). This nadir, however, may be sufficient to maintain the diurnal rhythmicity and sensitivity of 5-HT$_{2C}$ receptors in depression, even in the presence of elevated glucocorticoids. Moreover, there is a diurnal variation in performance of various neuropsychological tasks in normal and depressed individuals; however, the variations are often reversed in patients with depression (Moffoot et al., 1994). This nadir, however, may be sufficient to maintain the diurnal rhythmicity and sensitivity of 5-HT$_{2C}$ receptors in depression, even in the presence of elevated glucocorticoids. Moreover, there is a diurnal variation in performance of various neuropsychological tasks in normal and depressed individuals; however, the variations are often reversed in patients with depression (Moffoot et al., 1994). Some tasks, particularly those involving short-term memory, are dependent on hippocampal processing, and hence the diurnal expression of the 5-HT$_{2C}$ receptor may be an important factor in the production of these diurnal differences.

5-HT$_{2C}$ receptor mRNA is also expressed in extra-hippocampal sites, including the SCN, which generates regulates diurnal rhythms; however, we found high expression limited to a few cells around the dorsal cap of the SCN, along with lower expression in a subgroup of cells within the body of the nucleus. This distribution contrasts with high expression throughout the SCN reported by others (Roca et al., 1993). Whatever the cause of the discrepancy, no circadian rhythm of receptor gene expression was observed in any SCN subfield, and thus 5-HT$_{2C}$ receptors seem unlikely to be directly involved in or responsive to SCN rhythms. Most other loci of 5-HT$_{2C}$ receptor mRNA showed no diurnal changes; the exceptions of the BNST and the PVN are discussed below. The rhythm of 5-HT$_{2C}$ was selective in as far as no circadian changes in 5-HT$_{1A}$ receptor mRNA expression in the hippocampus were documented.

**GR and MR rhythms**

Both MR and GR mRNA expression in the hippocampus show circadian variation (Herman et al., 1993; Holmes et al., 1995a), findings confirmed here. A monophasic rhythm of both transcripts was seen, with the data fitting better with other diurnal processes (and the corticosterone rhythm) than the biphasic rhythm of MR reported previously by Herman et al. (1993). GR mRNA was clearly suppressed with by fixed-replacement, suggesting sensitive autoregulation (Burnstein et al., 1991). In
food-restricted rats, however, there was clear divergence from the expected inverse relationship between corticosterone levels and GR gene expression, with overall hypersecretion of corticosterone associated with increased GR mRNA in CA1 at some time points and maintained expression at all others. These data suggest that the increase in GR gene expression reflects other factors (stress, neurotransmitter release) in food restriction, again producing a mismatch, this time between corticosteroid receptors and their ligand. The MR mRNA rhythm was also abolished by fixed-level corticosterone replacement, suggesting that glucocorticoids are important; however, MR levels were not reduced to the usual diurnal nadir and clearly other cues are important in MR mRNA control. Again, food restriction disrupted MR diurnal variation, effects that may interfere with the normal MR-associated facilitation of hippocampal neuronal activation (Joëls and de Kloet, 1991). Why GR and MR (and 5-HT$_{2C}$ receptors) in CA3 should be exempt from diurnal variation and other regulatory influences in this study and others remains an unexplored anomaly. The various promoters of the MR gene show some site-specific expression and may underlie such effects (Kwak et al., 1993).

**HPA axis regulation**

The highest hippocampal 5-HT$_{2C}$ receptor mRNA expression is in ventral CA1 and the subiculum, areas showing circadian changes. Efferents from the subiculum project to the PVN, either directly (Kiss et al., 1983) or via the BNST (Herman et al., 1994). Lesioning of the fimbria-fornix pathway to the BNST has been reported to abolish the circadian rhythm of glucocorticoids (Fischette et al., 1980), although this has been contested (Bradbury et al., 1993). It is therefore possible that changes in subicular 5-HT$_{2C}$ receptor activity could alter the recognized hippocampal regulation of HPA axis activity (Jacobson and Sapolsky, 1991). Interestingly, the BNST relay is also under serotonergic control, and here too 5-HT$_{2C}$ receptor mRNA is highly expressed and shows a diurnal cycle. Moreover, the PVN expresses 5-HT$_{2C}$ receptor mRNA,

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**Figure 7.** The effect of pulsatile corticosterone replacement on the diurnal rhythm of 5-HT$_{2C}$ receptor mRNA expression in ventral CA1 of the hippocampus and plasma corticosterone levels. Sham-operated controls (square) compared with adrenalectomized rats with corticosterone replacement (circle). A, Sham-operated controls; B, corticosterone injection (20 mg/kg, s.c.) at 8 A.M. (8); C, corticosterone injection (20 mg/kg, s.c.) at 6 P.M. The arrow represents time of corticosterone injection. Receptor mRNA levels were determined by *in situ* hybridization histochemistry. The mean number of grains/subregion/rat was standardized to the expression observed in the control rats at 8 P.M. (20% (100%). Values represent mean ± SEM; n = 4. *p < 0.05 compared with 8–10 A.M. control value. <p><0.05 compared with 8–10 A.M. corticosterone replacement value. Time notation as in Figure 1 legend.
again with a circadian variation, although this is opposite (highest levels in the evening) to the hippocampus/subiculum and BNST (highest in the morning). This may be relevant to the negative influence of the hippocampus on the PVN. The pathway from the BNST to the PVN is GABAergic and inhibitory (Herman et al., 1994). Therefore, an increase in receptor number in the hippocampus and BNST may reinforce a decrease in receptor number at the PVN.

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