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Stress and Cocaine Addiction

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ABSTRACT
The hypothalamo-pituitary-adrenal (HPA) axis is involved in all aspects of cocaine self-administration. Corticosterone seems to be crucial for the acquisition of drug use since self-administration does not occur unless this stress hormone is increased above a critical reward threshold. Increasing circulating levels of corticosterone also augments sensitivity to low doses of cocaine, possibly from a sensitization-associated phenomenon involving dopamine, suggesting that exposure to stress can increase individual vulnerability to cocaine. Drugs affecting the synthesis and/or secretion of corticosterone decrease ongoing, low-dose cocaine self-administration. When higher doses falling on the descending limb of the cocaine dose-response curve are self-administered, plasma corticosterone can still reach this reward threshold even when synthesis is inhibited and drug intake is not affected. Corticotropin-releasing hormone (CRH) seems to play a more prominent role in the maintenance of cocaine self-administration and may even be involved in the incentive motivation for the drug. Corticosterone and CRH are also critical for the stress- and cue-induced reinstatement of extinguished cocaine-seeking behavior. Therefore, cocaine self-administration may represent an attempt to seek out specific sensations, with the internal state produced being very similar to that perceived by individuals who engage in risky, thrill-seeking behavior. During abstinence, exposure to stressors or cocaine-associated cues can stimulate the HPA axis to remind the individual about the effects of cocaine, thus producing craving and promoting relapse. Stress reduction, either alone or in combination with pharmacotherapies targeting the HPA axis may prove beneficial in reducing cravings and promoting abstinence in individuals seeking treatment for cocaine addiction.

The role of stress and the subsequent activation of the hypothalamo-pituitary-adrenal (HPA) axis in drug addiction has been under investigation in a number of laboratories for several years now. Subsequently, a number of excellent review articles have recently been published in an attempt to summarize the relevant research findings and to provide a rational explanation for these data (Bardo et al., 1996; Goeders, 1997, 2002; Kreek and Koob, 1998; Piazza and Le Moal, 1998; Koob, 1999; Shaham et al., 2000; Sarnyai et al., 2001). Since it is beyond the scope of this article to provide a comprehensive review of all of the literature related to stress and drug addiction, the reader is advised to consult the review articles listed above for a more detailed analysis. The purpose of this article is to review the work we have conducted investigating the role for the HPA axis in cocaine reward, to reconcile our data with the results obtained in other laboratories, and to present our own theoretical perspective on this subject.

When one considers the role of stress in cocaine reward and how activation of the HPA axis augments the motivation and/or vulnerability for cocaine use, the same questions continue to be asked. How can a stimulus (i.e., stress) that is generally regarded as something to avoid or escape actually increase the perception of reward associated with drug self-administration? Furthermore, how can a drug (i.e., cocaine) that in and of itself activates the HPA axis be one of the most reinforcing drugs ever studied? This article will examine these questions primarily in the context of cocaine self-administration in rats.

The HPA Axis and Cocaine

The HPA axis is initially activated by the secretion of corticotropin-releasing hormone (CRH) from the hypothalamus (Turnbull and Rivier, 1997; Sarnyai et al., 2001). CRH-containing neurons projecting from the parvocellular division of the paraventricular nucleus to...
the external zone of the median eminence release the peptide into the adenohipophyseal portal circulation in response to stress. The binding of CRH to receptors located in the anterior pituitary results in the synthesis of proopiomelanocortin, a large precursor protein that is cleaved to produce several smaller biologically active peptides, including β-endorphin and adrenocorticotropic hormone (ACTH). ACTH diffuses through the general circulation until it reaches the adrenal glands, where it stimulates the biosynthesis and secretion of adrenocorticosteroids (i.e., cortisol in humans or corticosterone in rats). The type I mineralocorticoid receptor has a high affinity for corticosterone and is usually fully occupied at basal concentrations of the hormone. This receptor also displays a high affinity for the mineralocorticoid aldosterone. The type II glucocorticoid receptor has a lower affinity for corticosterone and is more likely to be occupied when plasma corticosterone is elevated (e.g., during “stress”). This receptor also has a high affinity for the synthetic glucocorticoid dexamethasone.

Scientists have been aware of the existence of a complex relationship between HPA axis activation and the endocrine and neurobehavioral effects of cocaine for several years now (Piazza and Le Moal, 1998; Koob, 1999; Goeders, 2002). Acute, noncontingent cocaine administration increases plasma levels of ACTH, β-endorphin, and corticosterone (in rats) and cortisol (in nonhuman primates). These cocaine-induced increases in adrenocorticosteroids seem to be mediated by the cocaine-induced release of CRH from parvocellular neurons in the paraventricular nucleus (Sarnyai et al., 2001; Goeders, 2002). Acute cocaine administration decreases CRH-like immunoreactivity in the hypothalamus, hippocampus, and frontal cortex while increasing it in the amygdala, indicating that cocaine can also affect CRH activity in areas located outside the hypothalamus. In clinical studies (Mello and Mendelson, 1997), the acute intravenous administration of cocaine increases the secretion of cortisol and ACTH in chronic cocaine users, as does smoked cocaine. The intranasal administration of cocaine also increases cortisol secretion in male volunteers without a history of drug abuse. Plasma cortisol, β-endorphin, and ACTH are elevated in cocaine addicts on the day of admission into treatment centers, and cocaine-dependent individuals often display abnormal patterns of HPA axis activity. Clearly, cocaine itself stimulates many of the same neurochemical and hormonal systems also activated by exposure to stress. Accordingly, one might ask how a compound that directly stimulates the body’s responses to stress could also be so addictive. As will become evident below, stress and cocaine interact to affect reward differently during the various phases associated with the etiology of cocaine self-administration and withdrawal.

**The Acquisition of Cocaine Self-Administration**

During acquisition, an animal comes into contact with cocaine and its rewarding effects for the first time (Goeders, 2002). This is also when the animal learns to make the response that leads to cocaine delivery, thereby producing reinforcement. Environmental events that decrease the lowest dose of cocaine that is recognized by the animal as a reinforcer are considered to be events that increase vulnerability or the propensity for an animal to acquire self-administration. Acquisition can also be facilitated by events that decrease the time required to reach a specified behavioral criterion indicative of self-administration.

The ability of stressors to alter the acquisition of psychomotor stimulant self-administration has received considerable attention (Piazza and Le Moal, 1998; Goeders, 2002). The acquisition of amphetamine and cocaine self-administration is enhanced in rats exposed to a wide variety of either physical (e.g., social isolation or tail pinch) or social (e.g., exposure to the threat of an attack from an aggressive male rat) stress. We have investigated the effects of exposure to response-contingent (“controllable stress”) and noncontingent (“uncontrollable stress”) electric footshock on the acquisition of intravenous cocaine self-administration in rats (Goeders and Guerin, 1994). In these experiments, one rat from a group of three randomly received an electric footshock when it pressed a response lever that also resulted in the presentation of food (response-contingent shock). Although this resulted in a conflict between obtaining food reinforcement and avoiding footshock, these animals controlled if and when shock was delivered. Shock presentation for the second rat in each triad was yoked to the first rat so that the second rat received footshock regardless of whether it had pressed its food response lever at all (noncontingent shock). Therefore, these rats had no control over the delivery of the stressor. The third rat in each triad responded under the same schedule of food reinforcement as the other two rats but was never shocked. Self-administration was trained with an extremely low dose of cocaine during the first week of testing, and this concentration was subsequently doubled each week. When a full range of doses is investigated in this way, an inverted “U”-shaped dose-response curve is typically generated. In general, lower doses contained within the ascending portion of this curve are believed to be more related to cocaine reward than those falling on the descending limb, which is also affected by the unconditioned nonspecific effects of these higher doses of cocaine (Woods et al., 1987).

Exposure to uncontrollable footshock shifted the ascending limb of the cocaine dose-response curve upward and to the left, indicating that these rats were more sensitive to low doses of cocaine than rats exposed to response-contingent or no shock. Interestingly, increased sensitivity to cocaine was positively correlated with stress-induced increases in plasma corticosterone, and self-administration did not occur unless plasma corticosterone was increased above a critical level or threshold (Goeders and Guerin, 1996a; Goeders, 2002). Electric footshock did not affect responding maintained by higher doses of cocaine that fell on the descending limb of the dose-response curve, possibly because the cocaine infusions alone were sufficient to increase plasma corticosterone above this critical reward threshold in the absence of footshock. This phenomenon seems to be relatively specific for the acquisition of cocaine self-administration since, in our hands, neither exposure to footshock (Goeders and Guerin, 1996a) nor exogenous injections of corticosterone (Goeders and Guerin, 1999) affect ongoing self-administration. Thus, it seems that once this “reward threshold” is crossed, further stress-induced increases in plasma corticosterone are without additional effects on drug intake.

Since plasma corticosterone was positively associated with the ability of uncontrollable footshock to shift the ascending limb of the acquisition dose-response curve upwards and to the left, we next investigated the effects of exogenous injections of corticosterone on the acquisition of cocaine self-administration (Mantsch et al., 1998). Rats were treated daily, 15 min before each self-administration session with corticosterone (2.0 mg/kg i.p. suspended in saline) or saline. These injections began 2 weeks before the start of self-administration testing to mimic the stress experiment described above as closely as possible. Similar to what we observed with electric footshock, daily pretreatment with corticosterone also produced a leftward shift in the ascending limb of the dose-response curve for the acquisition of self-administration, indicating that corticosterone-treated rats were more sensitive to low doses of cocaine than were rats pretreated with saline. In a related experiment, rats were bilaterally adrenalectomized before acquisition testing (Goeders and Guerin, 1996b). This surgery effectively removed the final step in HPA axis activation, which is the synthesis and secretion of corticosterone. These adrenalectomized rats did not self-administer cocaine at any dose tested even though they quickly learned to respond on another lever for food pellets, indicating that the rats could still learn and perform the necessary lever-pressing response. These data suggest that plasma corticosterone may be critical for the acquisition of cocaine self-administration to occur in rats.

As reviewed above, corticosterone binds to both mineralocorticoid and glucocorticoid receptors. Therefore, rats were pretreated daily with the mineralocorticoid receptor agonist, aldosterone (0.1 mg/kg i.p.; 15 min), or the glucocorticoid receptor agonist dexamethasone...
(0.1 mg/kg i.p.; 60 min) as described above for corticosterone to distinguish between the potential roles for the two types of adrenocorticosteroid receptors in the effects of corticosterone on the acquisition of cocaine self-administration (Mantsch et al., 1998). Aldosterone treatment had little or no effect on the acquisition of self-administration, suggesting that mineralocorticoid receptors were not involved. Surprisingly, dexamethasone-treated rats did not acquire cocaine self-administration at any dose tested. However, at this relatively high dose, dexamethasone pretreatment completely inhibited the corticosterone response to cocaine and reduced basal corticosterone below detectable levels (Mantsch et al., 1998), most likely due to the activation of negative feedback mechanisms. Therefore, since the end result with respect to corticosterone secretion was similar, we had observed following adrenalectomy failure of these animals to acquire cocaine self-administration essentially replicated the results from our surgical adrenalectomy experiments (Goeders and Guerin, 1996b).

How does exposure to uncontrollable stress and elevated plasma corticosterone increase sensitivity to low doses of cocaine? This phenomenon probably occurs by a process analogous to sensitization (Piazza and Le Moal, 1998) whereby repeated intermittent injections of cocaine increase the behavioral and neurochemical responses to subsequent exposure to the drug. In fact, our acquisition experiments were specifically designed to test cocaine doses in an ascending order since exposure to higher doses of psychomotor stimulants can sensitize rats to lower doses, resulting in the acquisition of self-administration at doses of these drugs that would not otherwise maintain responding (Goeders, 2002). Interestingly, exposure to stressors or injections of corticosterone can also result in sensitization to the behavioral and neurochemical (e.g., nucleus accumbens dopamine) responses to cocaine (Rouge-Pont et al., 1995; Prasad et al., 1998), and these effects are attenuated in adrenalectomized rats (Prasad et al., 1998; Przegalinski et al., 2000) or when corticosterone synthesis is inhibited (Rouge-Pont et al., 1995). The ability of uncontrollable electric footshock or corticosterone injections to facilitate the acquisition of cocaine self-administration may therefore result from a similar sensitization phenomenon, perhaps involving dopamine (Goeders, 1997; Piazza and Le Moal, 1998). Although exposure to the stressor itself may be aversive, the net result is reflected as an increased sensitivity to low doses of cocaine. Therefore, if certain individuals are more sensitive to stress (Piazza and Le Moal, 1998) and/or find themselves in an environment where they do not feel that they have adequate control over this stress (Levine, 2000), then these individuals may be more likely to use cocaine and other drugs of abuse as well.

Although sensitization may be attenuated in adrenalectomized rats, this does not fully explain why these rats did not learn to self-administer cocaine when relatively high doses were tested since sensitization is less likely to be involved in the self-administration of these higher doses. Obviously, changes in a number of neurochemical and hormonal systems (e.g., CRH, ACTH, norepinephrine, and vasopressin) would be observed in adrenalectomized rats. Interestingly, adrenalectomy also reduces dopamine receptor binding (Biron et al., 1992) and dopamine transporter binding selectively in the shell of the nucleus accumbens (Sarnyai et al., 1998). Since dopamine is a major mediator of cocaine reward (Piazza and Le Moal, 1998; Koob, 1999), adrenalectomy might compromise cocaine-induced activity in critical brain reward systems by these decreases in dopaminergic neurotransmission. This reduced brain reward activity would, in turn, inhibit the acquisition of cocaine self-administration in adrenalectomized rats.

**The Maintenance of Cocaine Self-Administration**

During the maintenance of self-administration, the animal has already learned that the drug is a reinforcer and what responses are required for its subsequent presentation (Goeders, 2002). Mainte-
nence. Once the criteria for extinction are met or following a specified period of abstinence, the ability of specific stimuli to reinstate responding on the manipulandum previously associated with the delivery of drug infusions is taken as a measure of drug seeking. This reinstatement of drug-seeking behavior can be elicited by priming injections of the drug itself or by exposure to brief periods of intermittent electric footshock. Although the role for the HPA axis in stress-induced reinstatement was recently extensively reviewed (Shaham et al., 2000), the HPA axis does not seem to be involved in cocaine-induced reinstatement (Mantsch and Goeders, 1999; Goeders, 2002). However, clinical studies have demonstrated that simple exposure to environmental stimuli or cues previously associated with cocaine use can produce intense drug craving (O’Brien et al., 1992), suggesting that exposure to a physical stressor or a “taste” of cocaine itself are not necessary prerequisites for the development of craving in humans (Goeders and Clampitt, 2002). Preclinical investigations have also demonstrated that cue-induced reinstatement may indeed be an important and valid animal model of drug craving (Meil and See, 1996). Therefore, this section will focus on the involvement of the HPA axis in the cue-induced reinstatement of extinguished cocaine seeking.

Rats were trained to self-administer cocaine, with cocaine delivery paired with the presentation of a tone and the illumination of a house light (Goeders and Clampitt, 2002). Once a stable baseline of cocaine self-administration was observed, lever pressing was extinguished to less than 20% of baseline rates. During reinstatement testing, responding resulted in the presentation of a conditioned cue or reinforcer (i.e., the house light and tone previously paired with self-administered cocaine). The response-contingent presentation of the conditioned reinforcer reliably reinstated extinguished cocaine-seeking behavior, whereas the noncontingent presentation of the same stimulus did not. Increases in plasma corticosterone were evident during cocaine self-administration and during extinction and reinstatement testing. However, although plasma corticosterone returned to basal levels by the end of the session during extinction, it remained elevated through the end of the session during reinstatement, suggesting that cue-induced reinstatement was associated with HPA axis activation. Pretreatment with the corticosterone synthesis inhibitor ketoconazole reversed the conditioned reinforcer-induced reinstatement of extinguished cocaine-seeking behavior and also attenuated the conditioned increases in plasma corticosterone observed during reinstatement. Pretreatment with the CRH1 receptor antagonist CP-154,526 resulted in a similar decrease in cocaine seeking (Goeders and Clampitt, 2002). Recent preliminary data suggest that the benzodiazepines alprazolam and oxazepam also attenuate cue-induced reinstatement. Taken together, these data suggest an important role for the HPA axis in the ability of environmental cues to stimulate cocaine-seeking behavior in rats.

Since the corticosterone synthesis inhibitor ketoconazole was effective in blocking the ability of conditioned cues to reinstate extinguished cocaine seeking in rats, we conducted a small, open-label pilot study to determine the effects of chronic high-dose ketoconazole administration on cocaine craving in humans (unpublished observations). Five adult male and female cocaine users were enrolled into a 6-week study. The subjects reported to the clinic twice per week, and blood and urine were collected to determine plasma cortisol and the presence of cocaine. Subjective measures of anxiety, depression, and cocaine craving were also assessed, as were any adverse effects. The dose of ketoconazole was gradually increased from 600 to 1000 mg/day during the first 2 weeks and remained at 1000 mg/day for the remainder of the study. Chronic treatment with ketoconazole resulted in significant decreases in subjective reports of anxiety, depression, and cocaine craving in all five subjects. The subjects, however, reported that if they did use cocaine while on ketoconazole therapy, they could still get high, which is in agreement with other clinical (Ward et al., 1998) and animal data (Broadbear et al., 1999; Mantsch and Goeders, 1999; Filip et al., 2000) that suggested that ketoconazole does not block the subjective effects of cocaine. Nevertheless, two of these subjects were actually cocaine free at the end of the study even though no psychotherapy for substance dependence was provided. The only adverse effects reported were an upset stomach and nausea, which were easily mitigated by reducing the dose of ketoconazole. Although this experiment will have to be replicated in a larger, placebo-controlled, double-blind study, these data suggest that we are on the right track with our preclinical studies and that this line of research merits further study. The development of drugs that reduce HPA axis activity, especially in response to cocaine-associated cues, may represent an exciting approach for the discovery of novel pharmacotherapies for the treatment of cocaine addiction in humans (Goeders, 2002b).

Conclusions

The data reviewed above may seem somewhat counterintuitive. Cocaine can induce anxiety and panic in humans and anxiogenic-like responses in animals through its effects on CRH release (Goeders, 1997, 2002). Therefore, one might expect that augmenting HPA axis activity would produce an additive increase in the aversive effects of cocaine and reduce the motivation for the drug. During acquisition, however, exposure to aversive, stressful stimuli may actually sensitize individuals, making them more sensitive to cocaine reward. Once self-administration has been acquired, the positive aspects of cocaine reward probably mitigate the anxiogenic effects of cocaine.

However, another characteristic of cocaine self-administration is that drug delivery, and the resulting cocaine-induced stimulation of the HPA axis, is under the direct control of the individual. This is an important consideration since the controllability and predictability of a stressor significantly decrease its aversive effects (Levine, 2000). The individual controls when cocaine is administered and, therefore, when this activation of the HPA axis also occurs. This controlled activation of the HPA axis may result in the production of an internal state of arousal or stimulation that is actually sought by the individual (Goeders, 2002). This internal state may be analogous to novelty or sensation seeking that has been reported in humans (e.g., thrill seekers) and suggested to be involved in drug reward (Bardo et al., 1996; Dellu et al., 1996; Scourfield et al., 1996). Cocaine self-administration may represent an attempt to seek out specific sensations, with the internal state produced being very similar to that perceived by individuals who engage in risky thrill-seeking behavior (Goeders, 2002). During abstinence, exposure to stressors or cocaine-associated cues can stimulate the HPA axis to remind the individual about the effects of cocaine, thus producing craving and promoting relapse. Therefore, continued investigations into how stress and the subsequent activation of the HPA axis affect cocaine self-administration will result in the identification of more effective and efficient treatment for cocaine abuse in humans. Stress reduction, either alone or in combination with pharmacotherapies targeting the HPA axis, may prove beneficial in reducing cravings and promoting abstinence in individuals seeking treatment for cocaine addiction.

References


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