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BRAIN DERIVED NEUROTROPHIC FACTOR (BDNF) AND ITS INTRACELLULAR SIGNALLING PATHWAYS IN COCAINE ADDICTION

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ABSTRACT

Cocaine addiction is one of the severest health problems faced by Western countries, where there is an increasing prevalence of lifelong abuse. The most challenging aspects in the treatment of cocaine addiction are craving and relapse, especially in view of the fact that, at present, there is a lack of effective pharmacological treatment for the disorder. What is required are new pharmacological approaches based on current understanding of the neurobiological bases of drug addiction. Within the context of the behavioral and neurochemical actions of cocaine, this paper explores the contribution of brain derived neurotrophic factor (BDNF) and its main intracellular signaling mechanisms, including mitogen-activated protein kinase MAP kinase (MAPK/ ERK) and phosphatidylinositol 3-kinase (PI-3K) in psychostimulant addiction. Repeated cocaine administration leads to an increase in BDNF levels and enhanced activity in the intracellular pathways (PI-3K and MAPK/ERK) of the reward related brain areas, which applies especially several days following withdrawal. It has been hypothesised that these neurochemical changes contribute to the enduring synaptic plasticity that underlies sensitized responses to psychostimulants and drug-conditioned memories, leading to compulsive drug use and frequent relapse after withdrawal. Nevertheless, increased BDNF levels could also have a role as a protection factor in addiction. The inhibition of the intracellular pathways, ERK and Pi3-K, leads to a disruption in sensitized responses and conditioned memories associated with cocaine addiction and suggests new, potential therapeutic strategies to explore in dependence on psychostimulants.

INTRODUCTION

Cocaine use continues to increase in Western countries, and as such remains an important public health problem. Addiction to psychostimulants is a chronic disorder, characterized by craving, an intense desire to experience the effects of the psychoactive substance, and frequent relapse, even after prolonged drug-free periods, when all withdrawal symptoms have receded [1-3]. Despite various strategies for treatment that include antidepressant pharmacotherapy, dopaminergic agonists, antiepileptics or lithium, one of the main problems related to psychostimulant addiction is the absence of an effective pharmacotherapeutic agent for its treatment [4]. New therapeutic approaches, based on current understanding of the neurobiological bases of drug addiction are required.

Over recent few years, several lines of research have suggested that chronic drug exposure causes long-lasting neurochemical and cellular adaptations that result in enduring neuroplastic changes in brain circuitry, and which underlie compulsive drug consumption and relapse, even after long periods of abstinence [5-7]. Attention has mainly been focused on the effects of various drugs of abuse on cortical and subcortical areas, including the mesolimbic and mesocortical systems, comprising dopamine neurons in the ventral tegmental area (VTA), their projection to the nucleus accumbens (NAc), amygdala (A) and other forebrain regions [8,9]. Dopamine-dependent synaptic plasticity in the dorsal striatum has also been involved mostly in the late stages of addiction [8,10]. The role of glutamatergic neurotransmitter systems and interaction between dopamine and glutamate in determining the neuroplastic changes related to psychostimulant consumption warrant attention [11,12]. At the molecular level, the effects induced by chronic drug consumption also involve several intracellular signaling pathways [13,14] that lead to sensitization to drug effects [9] and modification in the learning and memory circuitry related to addiction [8]. Despite recent advances, however, the molecular bases of cocaine addiction have been only partially elucidated.

Recent evidence suggests that neurotrophins, such as brain-derived neurotrophic factor (BDNF) and its intracellular signaling pathways are also involved in neuroadaptive changes in the dopaminergic or glutamate systems that underlie psychostimulant abuse and dependence [15-21]. BDNF is a member of the nerve growth factor family, a group of secreted homodimeric proteins, isolated and characterized for the first time in 1982 [22]. BDNF signal transduction is mediated by binding to two different transmembrane receptors: the high-affinity Tyrosine Kinase Receptor B (Ntrk2 or TrkB) which specifically recognizes BDNF [23], and the low-affinity neurotrophin receptor p75(NTR) [24]. Both of these colocalize and modulate the neuron response to this neurotrophin. BDNF binding to the TrkB specific receptor triggers a ligand-dependent dimerization of the receptor, the autophosphorylation of specific intracellular tyrosine residues, and the activation of three different signal-transduction cascades. These include phosphatidylinositol 3-kinase (PI3-K), the mitogen-activated protein kinase (MAPK/ERK), and the phospholipase C-γ (PLCγ) cascades [25-27]. Some of these intracellular sygnaling mechanisms can also be activated through the stimulation of dopamine and glutamate neurotransmission [28,21], and there is evidence that cross-talk between those pathways may potentiate synaptic plasticity in drug addiction.

BDNF is expressed in several areas of the central nervous system, including the amygdala [29,30], the striatum [31], the prefrontal cortex [32], and its specific receptor TrkB is expressed in all mesencephalic dopaminergic neurons [33]. All these regions are involved in drug-induced neuronal responses. BDNF is a key element in the survival and differentiation of the dopaminergic system [34]. In the mature central nervous system, BDNF [35-38] and its intracellular pathways, MAPK/ERK [39-42] and PI3-K [43,44] play an essential role in modulating activity-dependent neuronal plasticity. In fact, these neurochemical systems are required to induce long-term potentiation, the basic mechanism of learning and memory that allow the external world to become encoded and stored as persistent molecular and structural modifications.

The aim of the present review is to examine the evidence supporting the involvement of the BDNF and its intracellular pathways in the neural mechanisms that underlie the development of psychostimulant addiction, understood as sensitization and conditioned drug responses, craving during withdrawal, and subsequent relapse. The identification of new neurobiological substrates in cocaine addiction is of considerable interest as it could provide new targets for the treatment of drug addiction.

BDNF AND ACUTE PSYCHOSTIMULANT EFFECTS

Several studies developed at the early 1990s to assess the behavioral and neurochemical effects of exogenous BDNF in different dopaminergic regions, and its interaction with a posterior single dose of psychostimulants. In adult rats, repeated BDNF infusions into the pars compacta of the substancia nigra (SN), potentiated the contraversive rotation behavior induced by posterior psychostimulant (amphetamine) administration. At the same time, neostriatal levels of dopamine metabolites, homovanilic acid (HVA) and 3.4-dihydroxyphenylacetic acid (DOPAC), were found to be increased in the BDNF-infused brain hemisphere. These behavioral and neurochemical effects suggested that BDNF is able to act on adult dopamine neurons *in vivo*, enhancing activity of nigrostriatal circuits and dopamine release [15,45]. Some years later, other studies assessed the effect of exogenous BDNF administration into two different regions of the mesolimbic dopaminergic system, the NAc and VTA, and its influence on locomotor activity induced by posterior cocaine administration. The results showed that cocaine challenge induced a significant enhancement of locomotor activity in mice when administered the day after repeated intra-NAc and intra-VTA BDNF treatment. BDNF enhanced the initial stimulant effect of cocaine [19]. In contrast, other studies have found that although BDNF induced increased behavioral activity when administered repeatedly intra-VTA, no further increase was seen after subsequent cocaine injection [16]. Collectively, these data showed that administration of BDNF in nigrostriatal and mesolimbic dopamine pathways potentiates psychostimulant effects, increasing anatomically specific dopaminergic dependent behavior and neurochemical turnover in those brain regions.

Because the sole use of psychostimulants is able to enhance dopamine transmission in the mesocorticolimbic regions, various experimental studies have assessed the effect of cocaine on BDNF expression in these areas of the brain. Although an early study reported no effect of acute cocaine use on BDNF levels in the VTA, SN and hippocampus [16], a recent report revealed an enhancement in the expression of mRNA encoding for BDNF in the rat NAc shell, but not in the core, induced by acute

cocaine administration [18]. The enhanced BDNF in this specific striatal area is consistent with the role of the ventrodioventral NAc compartment, the shell, the site of action for natural rewards such as food [46] and psychoactive drugs [47]. In the prefrontal and frontal cortices, a transient increase in the BDNF mRNA expression 2-4 hours after a single cocaine injection was also reported [48]. The increased expression of BDNF in some brain areas after acute psychostimulant administration is consistent with the activity-dependent cocaine induced changes in the expression of BDNF as an immediate early gene [49]. The role of psychostimulants on BDNF expression has been confirmed using heterozygous BDNF (+/-) knockout mice, which display half of the wild-type BDNF levels and provide a good model wherein to study the lifelong variation at BDNF locus. Even though heterozygous BDNF (+/-) mice showed results in locomotor activity equivalent to wild-type BDNF (+/+) [50], BDNF heterozygous animals displayed less locomotion than the wild-type animals after a single cocaine injection [51].

BDNF AND COCAINE INDUCED SENSITIZATION

It is now well established that drugs of abuse, such as cocaine, administrated intermittently and repeatedly, can produce sensitization, an enhancement of some drug related responses [52]. In animal models, sensitization can be measured by assessing the increase in locomotor behavior after repeated cocaine or amphetamine administration. The effects of a well established sensitization are long-lasting, and can be observed from several weeks to one year, after the last exposure to the drug [9,53]. As Robinson and Berridge hypothesized in their incentive-sensitization theory, sensitization is thought to underlie important aspects of vulnerability to drug addiction, craving during withdrawal and relapse in humans [9,53]. In rodents, sensitization was shown to enhance predisposition to psychostimulant self-administration [54] and facilitate the reinstatement of drugs after extinguished self-administration [55]. Moreover, there is a possibility that sensitization could contribute to psychotic symptomatology (eg. drug induced paranoia) among psychostimulant abusers and addicts, and even to the risk of schizophrenia in vulnerable individuals [56]. Recent research has suggested that BDNF could play some part in the neuronal changes that underlie sensitization following repeated psychostimulant administration.

In an early study, BDNF was infused for two weeks into two brain areas, the NAc and VTA, before rats underwent a treatment of cocaine sensitization. BDNF-treated animals showed a progressive increase in locomotor activity after repeated intra-NAc and intra-VTA cocaine injections, compared with vehicle-infused animals. These results suggested that previous infusions of BDNF into mesolimbic dopamine areas exert a potent effect in cocaine induced sensitization, measured as locomotor activity [19]. Recent experimental designs have studied the neurochemical changes underlying the behavioral effects of repeated cocaine treatment. The increase in locomotor activity and sensitization induced by repeated doses of cocaine was associated with enhanced levels of mRNA encoding BDNF in the rat NAc shell, but not in the core or in the hippocampus [18]. These results were consistent with the discrete roles of the NAc shell and core and the preferential involvement of the shell in the expression of cocaine sensitization [57]. Locomotor sensitization to repeated cocaine administration was also studied in heterozygous BDNF knockout mice compared with their wild-type littermates. Although there were no differences in locomotor activity between groups at baseline,

BDNF knockout mice were less sensitive to the locomotor stimulant effects of cocaine and showed a delay in the development of sensitization [19]. Together, these results suggest that, after repeated cocaine administration, the changes in BDNF expression, especially in the VTA and NAc-shell, could play a role in the development of sensitizing effects of this drug of abuse (see figure 1).

It has been suggested that the increase in BDNF expression induced by cocaine is mediated through dopamine D1 receptor activation [58]. In turn, it appears that BDNF can strengthen cocaine induced behavioral sensitization by controlling the expression of specific genes, such as the D3 dopamine receptor. One of the functions of D3 receptor is the modulation of the actions of D1 and D2 postsynaptic dopamine receptors [59]. D3 expression is elevated in the striatum in chronic cocaine abuse [60]. Using lesions or mice lacking BDNF, it has been shown that BDNF from dopamine neurons is crucial in triggering dopamine D3 receptor expression [48,61,62], and the induction of D3 occurs mostly in the core of the NAc and in the dorsal striatum, two areas where D3 is normally almost totally absent [61,62]. Pharmacological treatment using highly selective D3 lingands specifically reduces responses associated with cocaine consumption [63,64]. These findings suggest that BDNF may have a role in determining some pathophysiological conditions such as drug addiction [60,65].

BDNF can also act as a neuroprotection factor in drug addiction by activating homeostatic mechanisms that can counteract the effects of the chronic drug use. In fact, BDNF can induce the expression of neuropeptide Y and preprodynorphin in the striatum and NAc [62,66] and their increase may attenuate the effects of addictive drugs, whereas a decrease potentiates the effects of the drugs [14]. It is well known that BDNF [67] has a role in neuronal survival by providing the necessary neuronal trophic support and having a neuroprotective effect on pathological conditions, such as mood disorder [68,69]. According to these data, the increased expression of BDNF in cocaine addiction can enhance neuronal resilience, especially in reward related areas, thus counteracting the pathological effects of the repeated drug consumption.

BDNF AND CONDITIONED RESPONSES TO COCAINE

Environmental stimuli that are closely associated in time and space with the effects of drugs of abuse can acquire secondary reinforcing properties through a process of classical conditioning. The conditioned stimuli have in themselves the ability to elicit the emotional responses that were induced by the drug during active consumption, and maintain drug seeking behavior and relapse, even after long-term abstinence [70]. BDNF is a growth factor involved in synaptic plasticity [36,37,71,72] and in cellular events, such as long term potentiation (LTP) [35,38], thought to underlie contextual learning in the hippocampus [73] and conditioned responses in the amygdala [30,74]. Based on its functional ability, it has been suggested that the increased BDNF released during repeated psychostimulant intake might also have a role in the neuronal mechanism that underlies the conditioned responses to psychostimulants.

In an early study, Horger and coworkers [19] assessed the ability of BDNF to modify the reward related properties of the cocaine associated stimuli. Intra-NAc BDNF infusions strengthened the ability of a stimulus to act as a conditioned reinforcer and

also increased the cocaine-induced response to the conditioned reinforcer. The increased cocaine effects in BDNF-treated rats persisted for more than a month after the BDNF infusions had finished. Horger's et al research supports the hypothesis that BDNF promotes long-lasting changes in the mesolimbic dopamine system, by activating mechanisms of associative learning that underlie the persistent addictive behavior that endures long after withdrawal [19]. These results were later confirmed by a classic Pavlovian procedure that showed that mice repeatedly receiving cocaine in a particular environment showed hyperactivity after subsequent exposure to the drug-paired environment. The increased conditioned responses were associated with enhanced mRNA BDNF expression in the VTA which, in turn, modulate the expression of the D3 receptor in the NAc. Hyperactivity was not elicited by repeated cocaine administration or exposure to a new environment, and the authors assumed that the conditioned stimuli progressively acquired an emotional component associated with incentive and motivational properties [75]. The role of BDNF in drug-associated stimuli was further confirmed in heterozygous knockout mice using a conditioned place preference paradigm (CPP). BDNF (+/-) mice showed attenuated effects of cocaine reward and a decreased ability to learn a new association between the drug and the place where it was administered [51]. Overall, these results suggest that BDNF modulates synaptic morphology and plasticity underlying the learning processes [36,37,71,72] which strengthen conditioned responses to cocaine. Moreover, the decrease in the effects of cocaine on behavior and reward in BDNF deficient mice suggest that the human BDNF allelic variant, underlying individual variability in BDNF expression, can contribute to differences in human vulnerability to cocaine addiction [76].

BDNF, CRAVING AND RELAPSE IN COCAINE ADDICTION

One of the major clinical problems in cocaine addiction is relapse. This is often triggered by the subjective state of craving that appears during withdrawal, and precedes and accompanies drug-seeking behavior. Clinical evidence has shown that withdrawal is a critical period in addiction, during which sensitization to drug-associated environmental cues increases, triggering craving and heightening vulnerability and the risk of relapse [2]. During withdrawal, significant neuroadaptation occurs in the reward circuitry, including the molecular, cellular [5,8,14,77,78] and morphological synaptic changes [8,13] that have been associated with behavioral sensitization [79] and to mechanisms of learning and memory [10,80]. Recent experimental studies have suggested that changes in BDNF expression during withdrawal may mediate some of the synaptic modifications underlying the incubation of craving and subsequent relapse into drug consumption.

In experimental models of craving and relapse, responsiveness to cocaine cues increases progressively during withdrawal. In one of these studies, rats were trained to self-administer cocaine or sucrose for several days during which each reward was paired with a cue. After cocaine withdrawal, behavioral measures of lever pressing during extinction and cue-induced reinstatement of reward seeking (two different tests of cocaine craving), were progressively increased over 90 days or longer. It was found that BDNF levels rose significantly and progressively in the VTA, the NAc and the amygdala during withdrawal from cocaine, but not from sucrose. It has been suggested that increased BDNF during psychostimulant withdrawal may mediate neuronal

plasticity leading to synaptic modifications that underlie enhanced responsiveness to cocaine cues and compulsive drug seeking in addicts [17]. Based on these data, the role of BDNF in cocaine withdrawal was further studied by the same laboratory in a later work using the same animal model, but including, after the training period, an exogenous BDNF infusion into the VTA and the SN. Intra-VTA, but not intra-SN infusions of BDNF progressively enhanced cocaine seeking after withdrawal. The responses to cocaine cues were higher 30 days after withdrawal than 3 days after withdrawal [20]. It is well established that the VTA is the site of action of the primary excitatory inputs, which come from the PFC and the amygdala (see figure 1), two regions of the brain activated by drug associated cues [81]. The rise in BDNF levels during withdrawal may facilitate synaptic plasticity in the VTA dopamine neurons during withdrawal, which, in turn, facilitates drug associated memory and responses to conditioned cues leading to compulsive drug seeking and relapse.

The role of BDNF in synaptic plasticity of the midbrain VTA dopamine neurons during cocaine withdrawal has been further confirmed using a neurophysiological model. In VTA slices obtained from rats after withdrawal, weak presynaptic stimuli (WPS) administered on dopamine neurons resulted in a persistent increase of excitatory postsynaptic potentials (EPSP). The enhanced VTA neuronal responses were found 10-15 days after cocaine withdrawal; however, they were not detected 1 day after withdrawal. This shows that, during withdrawal, VTA dopamine neurons become increasingly excitable and susceptible to the induction of long-term potentiation (LTP). At the same time, BDNF levels were found to be increased in VTA tissues after 10-15 days of withdrawal, but were not detected 1 day after withdrawal. Moreover, when exogenous BDNF was applied to the VTA, persistent potentiation in dopamine neurons activity was observed both in naïve rats and after one day of withdrawal. These results suggested that BDNF was needed for the induction, expression and maintenance of LTP in VTA synapses. [82]. It is well established that LTP is a basic model for cellular processes that underlie information storage with the neural systems through the formation of new synapses and remodeling the existing ones [83]. BDNF plays a critical role in modulating synaptic plasticity in learning and memory processes [36,37,71,72]. Collectively, these data suggest that increased BDNF levels in VTA neurons during withdrawal may result in synaptic remodeling and sensitization which, in turn, enhance cue-associated excitatory inputs in this region of the brain contributing to compulsive drug seeking and relapse (see figure 1).

The amygdala expresses high levels of BDNF [29,30] and repeated injections of psychostimulants, such as cocaine [17] or amphetamine [84,] induce up-regulation of BDNF expression in the basolateral nucleus of the amygdala (BLA), the medial NAc and small zones in the dorsal striatum. The amygdala is a limbic nucleus which plays an important role in regulating motivational states, and different subnuclei in this structure mediate different learning and emotional processing. In particular, the central nucleus (CeA) and the basolateral nucleus (BLA) of the amygdala have different roles in conditioned learning in drug addiction [85]. The BLA has reciprocal projections to the nucleus accumbens core enabling it to influence reward related behavior. It is accepted that the BLA is responsible for emotional Pavlovian conditioning and mediate reward related learning, the motivational effects of emotionally significant stimuli and cue-elicited drug-seeking behavior [86,87]. Stimulation of the BLA can modulate the induction and maintenance of hippocampal long-term potentiation (LTP), the essential mechanism in learning and memory [88]. Taken together these data suggest that

enhanced BDNF activity following long-term abuse or dependence of psychostimulants can play an essential role in the determination of enduring neuroplasticity in these limbic structures (see figure 1). Such neuronal changes can account for emotional and environmental conditioned learning related to psychostimulant consumption, which can trigger a relapse even after long-term abstinence.

In humans, BDNF levels can be assessed in serum and there is evidence that serum BDNF levels correlate with levels of BDNF in the central nervous system [89]. To our knowledge, there is only one study reporting the effects of withdrawal from stimulant abuse on BDNF levels in humans. This study found significantly elevated plasma BDNF concentration in patients having a history of chronic methamphetamine abuse. The results of this study cannot be related to the history of comorbid psychiatric illness, addiction to drugs or other organic diseases which can modify BDNF expression, because patients with such conditions were excluded. The study suggests that BDNF may play a role in the effects of methamphetamine abuse in humans [90].

INTRACELULAR SIGNALLING PATHWAY OF BDNF

Through its high affinity TrkB receptor, BDNF leads to the activation of three intracellular signal transduction systems, including the MAP kinase signal transduction cascade (MAP kinase/ERK), PI3-kinase pathway and phospholipase [25,26,27] (see figure 2). It has been suggested that the role of BDNF in cocaine addiction is mediated, at least in part, through these intracellular signaling pathways.

MAP-Kinase cascade, cocaine addiction and relapse

Recent studies have demonstrated that ERK, the major effector of BDNF, is also activated by dopaminergic agonistic activity through D1 receptor [21,58,59], interacting with NMDA glutamate receptors and with a partial contribution of D2 dopamine receptors [21,41,91]. Since ERK is a common element for BDNF, dopamine and glutamate intracellular pathways, there appears to be a large degree of cross-talk between the signaling mechanisms and this might play a crucial role in drug addiction (see figure 2).

Acute cocaine administration induces a rapid and time-dependent increase in ERK phosphorilation (activation) in the dorsal striatum, in addition to the NAc core and shell [58,91,92]. Recent studies have shown that acute cocaine administration also activates ERK in other regions of the reward circuitry, including the NAc shell and core, the bed nucleus of the stria terminalis, the CeA [93,94], the basolateral, basomedial and medial posterodorsal amygdala [93], as well as in the prefrontal cortex [94]. In addition, inhibition of ERK activity impairs the rewarding properties of acute cocaine administration [91].

Chronic cocaine treatment (twice daily via intraperitoneal for 10 days) leads to a sustained increase in ERK activity in the VTA, although this change was not observed in the substantia nigra, frontal cortex and NAc. The increase in ERK activity in response to chronic cocaine administration was attributable to an enhanced phosphorylation state with no change in total ERK immuno-reactivity. In addition, repeated BDNF infusions into the VTA induce a decrease in ERK levels with no change

in ERK activity. This suggest that BDNF is able to elicit a homeostatic response in VTA cells that prevents any additional increase in ERK with repeated cocaine administration and returns ERK activity to control levels [28,94]. These findings support the hypothesis that BDNF, but not ERK, can act as a neuroprotection factor, attenuating chronic cocaine effects by reducing the capacity of VTA neurons to respond to repeated drug exposure [28].

Based on the acute and chronic effects of cocaine on ERK activity, several authors have studied the possible role of ERK in different models of cocaine addiction. PD98059, a MAP kinase kinase (MEK) inhibitor, through microinjection into the VTA before repeated cocaine exposure, was used to asses the role of ERK in behavioral sensitization. Although PD98059 had no effect on the acute behavioral response, it impaired the development of behavioral sensitization after chronic cocaine administration [16]. Consistent with these results, later studies reported that SL327, another inhibitor of ERK phosphorilation, prevented locomotor sensitization and had a limited effect on the acute locomotor responses to cocaine. These reports suggested that ERK contributes only in a minor way to acute locomotor effects or to the expression of sensitized responses to psychostimulants, whereas it is crucial for the acquisition of sensitized responses [95,96]. Considering the role of the Ras/MAP kinase signal transduction cascade in neuroplasticity [97], ERK could contribute to the neuronal changes in the NAc and VTA that are responsible for the acquisition of sensitized responses that underlies cocaine addiction in humans [96]. Taking into account the role of the two predominant ERK isoforms, elimination of ERK1 leads to an increase in ERK2 and facilitates cocaine-induced psychomotor sensitization [95], suggesting that genetic variants that may affect the expression of these isoforms could lead to vulnerability to cocaine addiction.

During the protocol used by Valjent in 2006 to study cocaine sensitization, mice showed an association between the context and the effects of the drug. Animals displayed conditioned locomotor responses in the environment previously paired with cocaine, even in the absence of the drug. These conditioned locomotor responses have many similarities with Pavlovian conditioning, by which environmental cues become associated to the effects of the drug. The conditioned responses were completely abolished in mice pre-treated with SL327 before each injection with cocaine, suggesting a crucial role for ERK in these responses [96]. A conditioned place preference paradigm (CPP) was used for a more detailed study of the role of ERK in the association between environmental stimuli and drug abuse. After behavioral conditioning was established, there was also a significant increase in ERK activity in the NAc core but not in the NAc shell [98]. The selective increase of ERK in the NAc core is consistent with the involvement of the reward regions in conditioned emotional responses and in cue-elicited drug seeking [86,87], while the NAc shell is involved in the unconditioned effects of cocaine [47]. The administration of intra-NAc infusions of U0126, an ERK kinase inhibitor, blocked the expression of the preference for the environment previously paired with cocaine without affecting measures of locomotion, and prevented the activation of the ERK signaling pathway. Blockade of the place preference conditioning lasted for 14 days after the injection of different MEK inhibitors [98]. Disruption of conditioned place preference induced by ERK cascade inhibitors was also reported after repeated administration of amphetamine [99] and MDMA [100]. Taken together, these findings suggested that ERK intracellular cascade in the NAc

core is part of the molecular mechanisms for drug-paired contextual cue memories, by which environmental stimuli exert a motivational influence on drug-seeking behavior.

ERK is also involved in the neurobiological and behavioral changes during cocaine withdrawal, mediating the BDNF-induced potentiation of cocaine seeking in response to conditioned stimuli [20]. Inhibition of ERK phosphorilation in the central amygdala (CeA) after 30 days withdrawal decreased cocaine seeking in response to drug cues, while stimulation of ERK activity enhanced cocaine seeking induced by cues [101]. It has been hypothesised that the increase in ERK phosphorilation in the CeA from exposure to cocaine cues during withdrawal may be mediated by an increase in glutamate activity through the NMDA receptor [41]. These findings suggest that activation of ERK pathway during withdrawal, in response to cocaine conditioned cues, is involved in synaptic plasticity underlying learning and memory that results in craving and subsequent relapse. Pharmacological intervention that prevents the effects of cocaine on ERK activity should be considered in the treatment of cocaine addiction [102].

It has been hypothesised by [103] that mechanisms similar to memory reconsolidation are operating during repeated drug administration and withdrawal, and the molecular mechanism of drug-conditioned effects has been evaluated on this basis. Valjent reported that suppression of cocaine-induced CPP by SL327, a MEK inhibitor, required the combination of cocaine administration and the drug-associated environment and did not result from extinction. According to these results, the reactivation of drug related memories appears to need the association of cocaine injection and the conditioned drug-paired environment, in contrast to reconsolidation of other types of memories achieved by exposure to the conditioned stimulus alone. In the same study, mice were also treated with anisomycin, a protein synthesis inhibitor, after being re-exposed to cocaine in the drug-paired compartment. Anisomycin abolished cocaine induced CPP suggesting that ERK exerts its effect through protein synthesis regulation [103]. In addition, cocaine induced locomotor sensitization cannot be reversed by cocaine re-exposure in the presence of anisomycin, supporting that cocaine conditioning and cocaine sensitization are two discrete behavioral responses that depend on different neurochemical mechanisms and even on different neuronal pathways [103].

PI3-K cascade and cocaine addiction

PI3-K is a lipid kinase and a second messenger for BDNF which plays a crucial role in the cellular mechanism of LTP, being necessary for the expression of LTP, although not for its induction and maintenance [43,44]. PI3-K can be a common pathway for the expression of multiple forms of synaptic plasticity such as dynamic modification of dendritic spines [44] and plays an important role in learning and memory [72,104]. Recently, there has also been evidence implicating PI3-K in cocaine addiction.

Cocaine sensitized rats, treated with the reversible inhibitor of PI3-K LY294002 on the challenge-dose day, did not show an increase in locomotor activity. Conversely, when rats were treated with LY294002 during the initial phase of repeated cocaine administration, they showed a significant increase in locomotor activity during the cocaine challenge. These results suggested that PI3-kinase is necessary for the expression of behavioral sensitization to cocaine but not for the induction and

persistence of the sensitized behavior [105]. This is in contrast to the ERK signal transduction cascade involved in the induction of behavioral sensitization, but not in its expression [16,96], suggesting that these two intracellular signaling mechanisms may play complementary roles in cocaine addiction.

Recently, the differential involvement of different brain structures in PI3-K dependent cocaine sensitization and its subsequent reversal has been evaluated. After repeated cocaine administration and withdrawal, rats showed an increase in locomotor behavior associated with enhanced p85α/p110 PI3-K activity in the NAc shell, measured after 23 days withdrawal. Administration of pergolide (a mixed D1/D2 agonist)/ondansetron (5-HT3 selective antagonist) after withdrawal reversed behavioral sensitization and normalized the enhanced PI3-K activity. At the same time, a PI3-K down-regulation and up-regulation in the NAc core and PFC, respectively, was reported. However, in these two regions of the brain PI3-K activity was not normalized following the reversal of cocaine sensitization. These results suggest that PI3-K in the NAc shell may be one of the key alterations underlying the establishment and long-term maintenance of cocaine sensitization [106]. The discrete expression of PI3-K in the NAc shell in response to cocaine sensitization and withdrawal further supports the differential roles of the NAc shell and core, with the former being involved in the expression of the sensitizing effects of cocaine [57].

CONCLUSIONS

Cocaine consumption leads to an increase in BDNF levels and enhanced activity in their intracellular pathways, ERK and PI3-K. These changes are observed in the reward related brain areas, including the NAc shell and core, the VTA, the central and basolateral nucleus of the amygdala and even in the PFC. These effects notably increase over the initial weeks of abstinence. BDNF, ERK and PI3-K can be activated by cocaine consumption, through dopaminergic and glutamatergic stimulation, together leading to increased gene expression which plays an essential role in synaptic plasticity. BDNF and its intracellular signaling mechanisms, ERK and PI3-K, in the VTA, NAc shell and the PFC may underlie sensitized responses to psychostimulants and cocaine seeking behavior after withdrawal. In the NAc core and the amygdala, the enhanced BDNF levels and ERK activity might be part of the molecular mechanisms underlying drug-paired environmental and cue memories in the context of drug-seeking behavior. All these neurochemical mechanisms could contribute to the transition from sporadic cocaine consumption to addiction and relapse even after long-term abstinence. In addition, the neurotrophin BDNF could also have some role as a protection factor in drug addiction. Finally, sensitization and memories associated with addiction to psychostimilants can be disrupted by administration of Ras/ERK and PI3-K cascade inhibitors which decrease cocaine seeking after withdrawal. These results suggest potential therapeutic strategies to be explored in the context of addiction.

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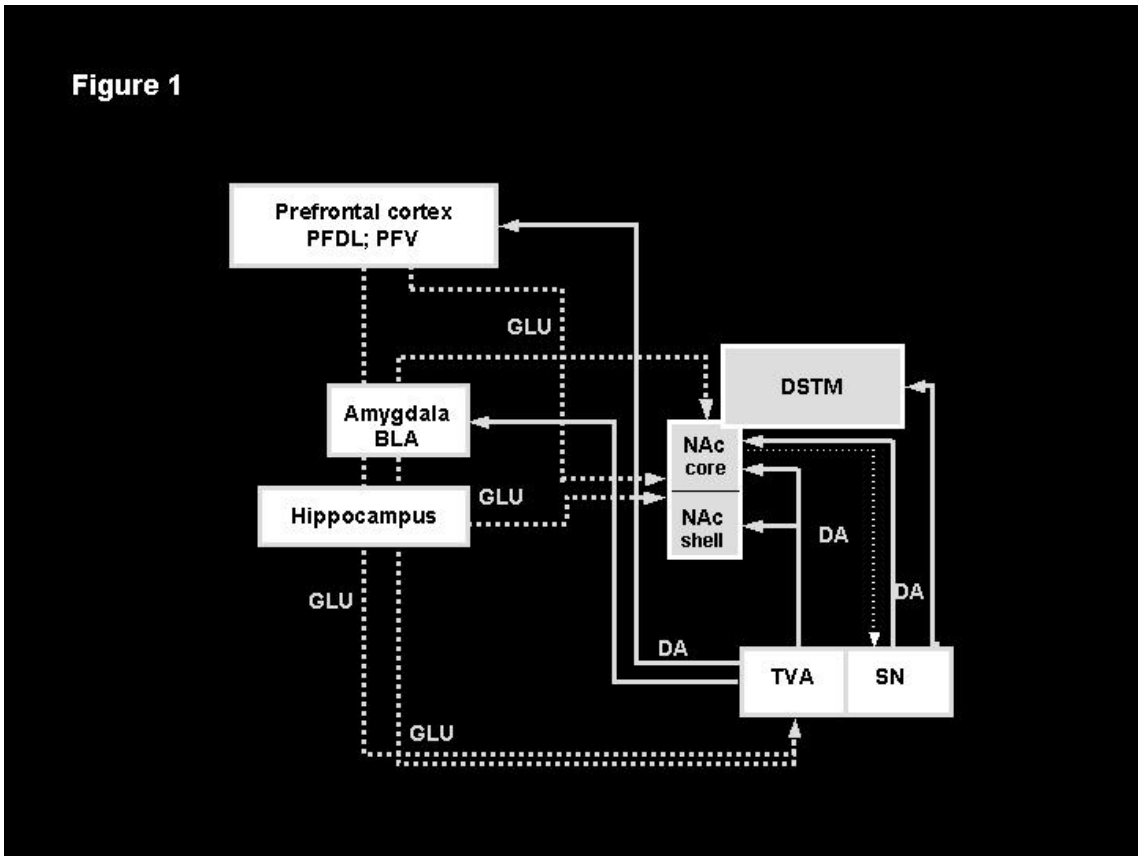

Figure 1. Basic circuitry expressing changes in BDNF levels in cocaine addiction. Includes the primary neurotransmitters, the topographic organization and interconnections between the reward related pathways, learning and memory pathways and circuits involved in cocaine seeking. The mesencephalic ventral tegmental area (VTA) projects its dopaminergic (DA) efferents to the limbic nuclei, the nucleus accumbens (NAc) core and shell, amygdala and hippocampus, and the dorsolateral prefrontal cortex (DLPF) and ventral prefrontal cortex (VPF). The hippocampus and amygdala, the latter through its basolateral subnucleus (BLA) and the DLPF and VPF cortex project their glutamatergic (GLU) efferents to the shell and core of the NAc, respectively. The figure also includes the dorsal striatum (DSTM) and its connexions with the substantia nigra (SN).

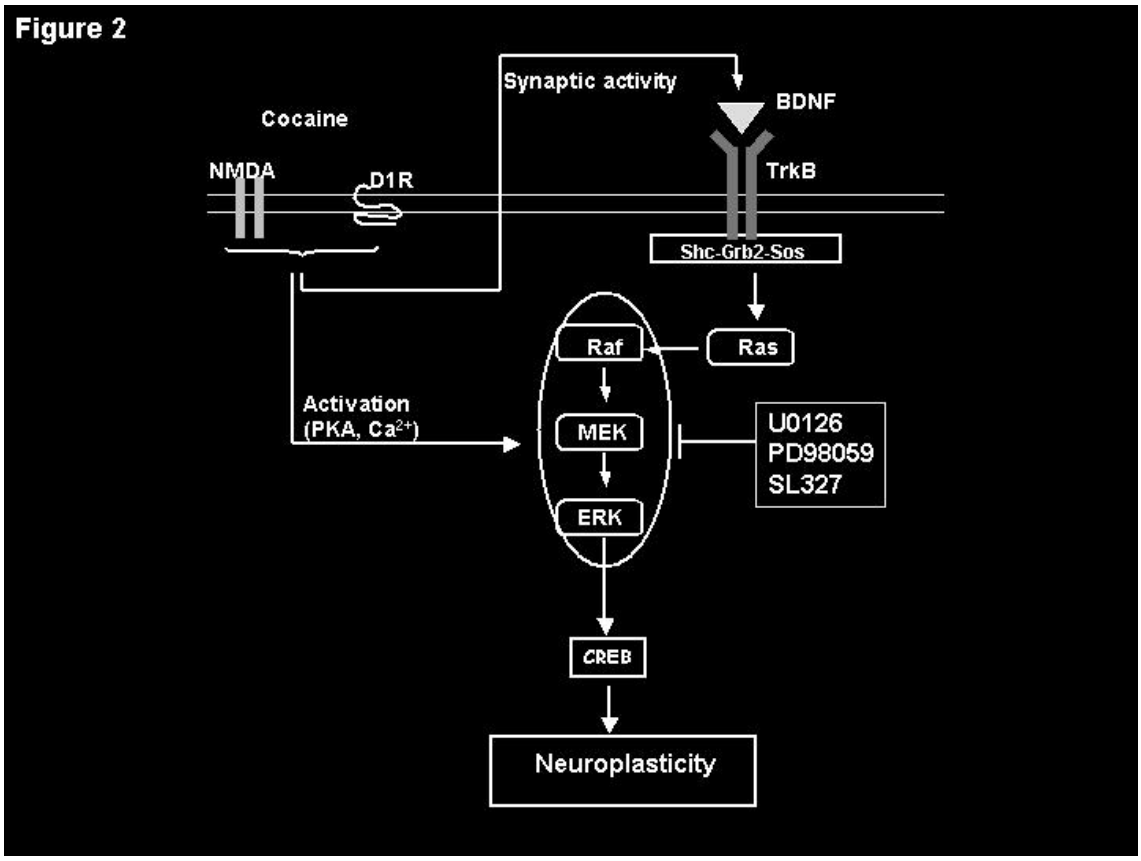

Figure 2. BDNF and the ERK intracellular signaling pathway. The figure includes one of the two BDNF signaling cascades involved in cocaine addiction and its interaction with dopamine and glutamate intracellular messengers. The BDNF signalling pathway is initiated by the binding of BDNF with the receptor TrkB. Once activated, the TrkB receptor autophosphorylates specific tyrosine residues within the intracellular domains. The phosphorylated tyrosines serve as protein interaction sites for Shc (SH2-containing adapter protein). Tyrosine phospshorylation of SHC subsequently triggers phosphorylation reactions that include Raf, MEK and mitogen-associated protein kinase (MAPK/ERK). The cyclic AMP response element-binding protein (CREB) is an important downstream mediator for BDNF function which triggers neuronal changes, neuroplasticity, etc. There is a cross-talk between the BDNF intracellular signaling mechanism and those of the glutamate and dopamine transmission, possibly between protein kinases (PKA) and Ca^{2+}. U0126, PD98059 and SL327 are inhibitors of the Ras/ERK signal transduction cascade.