Presynaptic Actions of D2-Like Receptors in the Rat Cortico-Striato-Globus Pallidus Disynaptic Connection In Vitro

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Watanabe K, Kita T, Kita H. Presynaptic actions of D2-like receptors in the rat cortico-striato-globus pallidus disynaptic connection in vitro. J Neurophysiol 101: 665–671, 2009. First published December 10, 2008; doi:10.1152/jn.90806.2008. The cerebral cortex, the neostriatum (Str), and the external segment of the globus pallidus (GPe) form a cortico-Str-GPe disynaptic connection, which is one of the major connections in the basal ganglia circuitries and a target of dopamine modulation. The aim of this study was to examine the actions of D2-like dopamine receptors (D2LRs) in this connection using rat brain slice preparations. Electrical stimulation of the frontal cortex evoked disynaptic inhibitory postsynaptic currents (IPSCs) in cesium-filled GPe neurons voltage-clamped at 0 mV. The IPSCs evoked by threshold stimulation were small, <10 pA. Bath or local applications of the D2LR agonist quinpirole to Str decreased the amplitude of the cortical stimulation-induced IPSCs. Electrical stimulation of Str evoked monosynaptic IPSCs in GPe neurons. Local application of quinpirole to GPe increased the Str stimulation-induced IPSCs. Bath application of quinpirole decreased the frequency of large miniature IPSCs (mIPSCs) that were considered to be evoked by local collateral axons of GPe neurons. These results suggested that activation of D2LRs increase the gain of the cortico-Str-GPe disynaptic connection, with the decrease attributed to activation of D2LRs in Str and GPe, and that both Str-GPe and GPe-GPe GABAergic inhibitions are under the control of presynaptic D2LRs.

INTRODUCTION

The cerebral cortex, the neostriatum (Str), and the external segment of the globus pallidus (GPe) form a cortico-Str-GPe disynaptic connection. This disynaptic connection might play a significant role in motor control in normal and in pathological conditions such as Parkinson’s disease because GPe projects to most of basal ganglia nuclei and controls their level and pattern of firing activity (Bolam et al. 2000; Kita 1994a/b, 2007; Kita et al. 2005; Mink 1996). The connection is a target for dopamine modulation because significant changes in GPe activity take place in parkinsonian patients and in experimental parkinsonian animals (Beric et al. 1996; Filion and Tremblay 1991; Pan and Walters 1988; Sterio et al. 1994; Wichmann and DeLong 2006). Various studies have suggested that nigral dopaminergic projections to Str and GPe modulate the activity of the cortico-Str-GPe connection in a rather complex manner. We intended to clarify some of issues regarding the actions of D2-like (mostly D2 and D4) dopamine receptors (D2LRs) in the connection. In Str, two opposing actions of D2LRs are possible, and in GPe, two types of GABAergic axons can be modulated by D2LRs, as summarized below.

Immuno-electron microscopy studies localized D2LRs on cortico-Str nerve terminals (Wang and Pickel 2002). Physiological studies reported that application of D2LR agonists decreased cortico-Str synaptic transmissions by decreasing glutamate release from the synaptic terminals (Calabresi et al. 1992; Flores-Hernandez et al. 1997; Hsu et al. 1995). It has also been well documented that Str neurons projecting only to GPe express high levels of D2LRs (Gerfen et al. 1990; Meador-Woodruff and Mansour 1991). Activation of D2LRs on Str-GPe projection neurons opened potassium channels and suppressed their firing (Freedman and Weight 1988; Greif et al. 1995). Thus activation of D2LRs on both cortical terminals and Str cells may suppress activity of the cortico-Str-GPe connection. An opposing action is also possible. Because the Str neurons projecting to GPe express D2LRs, their local collateral axons and axons in GPe are also likely to express D2LRs. In addition, fast-spiking GABAergic parvalbumin containing interneurons and cholinergic interneurons in Str and their axon terminals express D2LRs (Alcantara et al. 2003; Delle Donne et al. 1997; Lenz et al. 1994; Maurice et al. 2004; Wang et al. 2006). Activation of D2LRs on these axons would suppress GABAergic inhibitions on Str-GPe neurons and could augment activity of the cortico-Str-GPe connection. The first aim of this study was to determine how the two opposing actions of D2LR activation in Str affect the gain of disynaptic cortico-Str-GPe connection.

GPe neurons express mRNAs for D2LRs (Gerfen et al. 1990; Meador-Woodruff and Mansour 1991). Thus local collateral axons of GPe projection neurons might express D2LRs. The Str-GPe axons also express D2LRs, as mentioned above. Although sparse, GPe receives dopaminergic fibers from the substantia nigra pars compacta (Lavoie et al. 1989; Lindvall and Bjorklund 1979). Previous physiological studies have suggested that activation of D2LRs decrease GABA release (Floran et al. 1997) or GABAergic IPSCs in GPe (Cooper and Stanford 2001; Querejeta et al. 2001; Shin et al. 2003). However, it still remains uncertain whether D2LRs control only Str-GPe synapses or both Str-GPe and GPe-GPe synapses. The second aim of this study was to study this issue using whole cell patch-clamp recording from GPe neurons in rat brain slice preparations.

METHODS

Slice preparation

This study was performed in compliance with the National Institutes of Health Guide for Care and Use of Laboratory Animals. The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
Sprague-Dawley rats (16–21 days old) were anesthetized with an intraperitoneal injection of a mixture of ketamine (85 mg/kg) and xylazine (15 mg/kg). After decapitation, the brain was rapidly removed, and blocks containing the cortex, Str, and GPe were obtained. Oblique sagittal slices (400 μm thick) were cut from the blocks on a vibrating-blade microtome (Leica VT1000S, Leica Microsystems, Nussloch, Germany) in ice-cold oxygenated artificial cerebrospinal fluid (ACSF) containing (in mM) 126 choline chloride, 3 KCl, 1.24 NaH2PO4, 26 NaHCO3, 0.5 CaCl2, 6.3 MgSO4, 0.2 thiourea, 0.2 ascorbic acid, and 20 d-glucose, pH 7.4. The slices were incubated in ACSF containing (in mM) 126 NaCl, 3 KCl, 1.24 NaH2PO4, 26 NaHCO3, 2.4 CaCl2, 1.3 MgSO4, and 10 d-glucose, equilibrated with 95% O2-5% CO2 at pH 7.4 and 32°C for 1 h before recording.

Electrophysiological recordings

The slices were transferred to a recording chamber with oxygenated ACSF continuously perfused at a flow rate of ≈2 ml/min. The temperature of the recording chamber was kept at 32 ± 1°C. Whole cell recording pipettes with a tip diameter of ≈1.5 μm were pulled from 1.5 mm, thin-wall, borosilicate glass capillaries on a horizontal electrode puller (P-97, Sutter Instruments, Navato, CA). GABAAB-mediated inhibitory postsynaptic currents (IPSCs) and miniature IPSCs (mIPSCs) were recorded with pipettes filled with (in mM) 110 Cs2SO4, 5 tetraethylammonium, 0.5 CaCl2, 2 MgCl2, 5 EGTA, 5 HEPES, 5 Mg-ATP, 0.2% Neurobiotin, and 3 QX-314 with the pH adjusted to 7.2 with CsOH. Cs2SO4, tetraethylammonium, and QX-314 were used to block voltage-gated potassium currents and action potential generation. Neurobiotin was used to histologically confirm the locations of recorded GPe neurons. The resistance of these recording pipettes was 3–8 MΩ. All IPSCs and mIPSCs in this study were recorded from neurons voltage clamped at 0 mV. Neurons and recording pipettes were visualized using an infrared-differential interference contrast microscope BX50WI (Olympus, Tokyo, Japan), with a ×40 water immersion objective LUM Plan PL (Olympus) and a CCD camera (OLY-150, Olympus).

Whole cell recordings were obtained with an amplifier Axopatch-200B (Axon Instruments, Foster City, CA). The output of the amplifier was monitored on an oscilloscope HN-107 (HAMEG, East Meadow, NY). Signals were filtered at 5 kHz, digitized at 10 kHz with a computer interface ITC-18 (InstruTECH, Port Washington, NY), and stored on the hard disc drive of a Macintosh G4 computer, using the data acquisition and analysis system Axopatch 4.6 (Axon Instruments).

Postsynaptic responses

To evoke cortico-Str-GPe disynaptic IPSCs, triple stimulation (a train of 3 current pulses with 3-ms interpulse intervals, each pulse 200 μs in duration and ≈200 μA) was applied through a bipolar electrode (tip distance, 0.5 mm) every 10 s. The cathode of the bipolar electrode was placed on the subcortical white matter, and the anode was on the deep layer of the cortex. To evoke Str-GPe monosynaptic IPSCs, a train of 3 current pulses with 3-ms interpulse intervals, each pulse 200 μA in amplitude, was applied to the bath or locally to the cortex, Str, or GPe. For local application, a stainless steel tube with an inner diameter of ≈0.6 mm was used. The shaft of the tube was positioned parallel to bath flow and tilted ≈30 degree from the horizontal plane, with the orifice about 0.3 mm above the slice and 0.5 mm upstream to a desired drug application site. The quinpirole-containing (10–50 μM) ACSF was ejected (0.2–0.3 ml/min) from the tube (Fig. 3A). We assumed that the ejected quinpirole was diluted with bath ACSF before reaching the effective site of the slice, with the degree of the dilution dependent on factors such as relative location from the tube orifice.

Data analysis and statistics

All group data were expressed as a means ± SD and analyzed statistically using Student’s paired t-test. P < 0.05 was considered statistically significant. mIPSCs were analyzed using the Mini Analysis Program (Synaptosoft, Decatur, GA). Events were ranked by amplitude and interevent interval for the preparation of cumulative probability distributions within 1- to 3-min epochs for control and drug conditions. The cumulative probability distributions were compared with the Kolmogorov-Smirnov test in the Mini Analysis Program.

Chemicals

NBQX, CPP, (−)-(−)-quinpirole hydrochloride, (S)-sulpiride, TTX, and 2-[3-carboxypropyl]-3-amino-6-[4-methoxyphenyl]pyridazinium bromide (gabazine) were obtained from Sigma-Aldrich (St. Louis, MO). QX-314 was obtained from Alomone Labs (Jerusalem, Israel).

RESULTS

Cortical stimulation evoked IPSCs in GPe

Single electrical stimulation of the cortex in oblique sagittal slice preparations failed to evoke IPSCs in GPe neurons. However, stimulation of the cortex with triple current pulses did evoke IPSCs in GPe neurons, although the success rate was small—less than one neuron per 10 slices. IPSCs evoked by a threshold stimulus intensity were small (<10 pA) and had long latencies (23.8 ± 4.0 ms, n = 15). When the stimulus intensity was gradually increased, the response amplitude gradually increased, and the latency gradually shortened. The response amplitude and the latency became relatively stable after reaching a certain stimulus intensity (Fig. 1, A and B). The shortest latency and the largest amplitude of IPSCs observed with ±120-μA stimulus intensity was 16.8 ± 2.3 ms and 38 ± 5 pA (n = 15). Bath application of the ionotropic glutamate receptor antagonist mixture NBQX (10 μM) plus CPP (30 μM) or the GABAAB receptor antagonist gabazine (10 μM) blocked the IPSCs (Fig. 1C).

Effects of quinpirole on cortical stimulation-evoked IPSCs in GPe

Bath application of quinpirole (10 and 20 μM) significantly decreased (−60 and 45% of control, respectively) the amplitude of cortical stimulation-evoked IPSCs in GPe (Fig. 2, A and B). The decrease of the amplitude was associated with a 2- to 5-ms increase in the response latency. Quinpirole did not alter the input resistances of the neurons assessed by voltage pulses of 10-mV and 30-ms duration (Fig. 2C). Bath application of sulpiride (20 μM) blocked the quinpirole effects (Fig. 2E). Sulpiride itself had no significant effects on the IPSCs.

To assess effects of D2LR activation in Str, quinpirole was applied locally to Str through a stainless steel tube (Fig. 3A). Application of 10–50 μM quinpirole to Str significantly decreased the amplitude of the cortical stimulation-evoked IPSCs in GPe (Fig. 3, B–D). Local application of quinpirole, ≤50
Quinpirole (10–50 μM) was applied to the recording sites in GPe through a stainless steel tube with the orifice placed ~0.5 mm upstream of the bath flow similar to the Str application described above. Quinpirole significantly reduced the amplitude of IPSCs (Fig. 4, A–C). The reduction of the amplitude was accompanied by an increase in paired pulse ratios (PPRs), the ratio of the amplitude of IPSCs from the second test to the first conditioning stimulation; Fig. 4D). Similar experiments were performed with higher Str stimulus intensities to evoke large IPSCs with ~5 ms latency. Quinpirole significantly reduced the amplitude of IPSCs (Fig. 4, E–G) without a significant increase in PPRs (Fig. 4H). Quinpirole application to the recording site ≤50 μM did not alter the input resistances of the neurons (n = 10, data not shown).

Local application of quinpirole (20 and 50 μM) to the Str stimulus site also significantly reduced the amplitudes of long-latency IPSCs without altering their PPRs (Fig. 5, A and B). However, quinpirole (≤50 μM) failed to alter short-latency IPSCs (Fig. 5, C and D).

**Effects of quinpirole on Str stimulation-evoked IPSCs in GPe**

We examined effects of quinpirole application to GPe on Str stimulation-evoked IPSCs because these were more readily recorded than cortical stimulation-evoked IPSCs and because some loss of neurons during recording could be tolerated. The properties of Str stimulation-evoked gabazine-sensitive IPSPs in GPe have been studied previously. Low-intensity Str stimulation evoked long, ~8 ms, latency IPSCs that were considered to be evoked mainly by Str-GPe axons. High-intensity stimulation evoked short, ~5 ms, latency IPSCs that were composed of an early component evoked by intrapallidal collateral axons of GPe-Str projection neurons overlapped with the long latency component evoked by Str-GPe axons (Kita 2007; Ogura and Kita 2000). In this study, double stimulation of Str with 50-ms interpulse intervals was used to evoke IPSCs in GPe neurons in slices perfused with ACSF containing the AMPA/kainate receptor antagonist NBQX (10 μM) and the NMDA receptor antagonist CPP (30 μM). Long- and short-latency IPSCs were evoked by adjusting the stimulus intensity.
Quinpirole reduced the frequency but not the amplitude of mIPSCs

To examine whether quinpirole suppresses GABA release from synaptic boutons of intra-GPe collateral axons, mIPSCs were recorded from GPe neurons in the presence of NBQX (10 μM), CPP (30 μM), and TTX (1 μM). Only mIPSCs with amplitudes exceeding 10 pA were analyzed, and neurons exhibiting mIPSCs with frequencies exceeding 1 Hz were selected for this experiment (Fig. 6A). Gabazine (10 μM) application blocked the mIPSCs, confirming that they were mediated via GABAA receptors (data not shown). Bath application of quinpirole (5–20 μM) significantly decreased the frequency of mIPSCs (Fig. 6B) without changing their mean amplitude (Fig. 6C) or the amplitude distribution (Fig. 6D). Bath application of quinpirole ≤20 μM did not alter the input resistance of these GPe neurons (n = 5; Fig. 6C). It has been
showed that activation of presynaptic serotonergic receptors decreases GABA release in GPe. To test the possibility that quinpirole activates serotonin receptors on GABAergic terminals, slices were pretreated with 10 μM methysergide, a serotonin 1/2/5/6/7 receptor antagonist that blocks receptors on GABAergic terminals in GPe (Hashimoto and Kita 2008). Methysergide did not occlude 20 μM quinpirole effects on the frequency of mIPSPs (Fig. 6B).

**DISCUSSION**

The primary aim of this study was to clarify the effects of D2LR activation in the cortico-Str-GPe disynaptic connection. The results showed that D2LRs control the gain of the disynaptic connection in both Str and GPe through presynaptic mechanisms.

**Cortical stimulation evoked IPSCs in GPe**

Stimulation of the cortex in oblique sagittal slices cut from rat brains could evoke IPSCs in GPe neurons. There are two possible connections that could induce IPSCs: cortico-Str-GPe and cortico-GPe-GPe (Naito and Kita 1994). The following data suggest that the IPSCs were mediated by the cortico-Str-GPe disynaptic connection. The IPSCs were sensitive to bath application of either glutamate receptor or GABA<sub>A</sub> receptor antagonists. The latency of the IPSCs shortened with an increase in the stimulus intensity, and the latency matched those expected from the conduction time of the cortico-Str-GPe connection. The IPSCs evoked by threshold stimulation were small (<10 pA). This suggests that Str projection neurons evoke small IPSCs in GPe neurons, because their local collateral axons evoke small IPSCs in neighboring Str neurons (Czubayko and Plenz 2002; Jaeger et al. 1994; Koos et al. 2004) and that co-activation of a large number of Str neurons is required to inhibit autonomously active GPe neurons.

The yield of this experiment was low for two main reasons: only small numbers of the disynaptic connection survived in slice preparations, and Str neurons in slice preparations had very negative resting potential and required large excitatory postsynaptic potentials (EPSPs) to reach their spike threshold. The fact that we could observe IPSCs with triple but not with single stimulation is consistent with the second reason.

**Effects of quinpirole on cortical stimulation-evoked IPSCs in GPe**

Bath application of quinpirole decreased IPSCs, whereas sulpiride application antagonized the quinpirole effect. This observation suggested that the overall effect of D2LR activation was a decrease in the gain of cortico-Str-GPe connection. Activation of D2LRs in Str can inhibit Str projection neurons by presynaptically decreasing cortico-Str excitation (Calabresi et al. 1992; Flores-Hernandez et al. 1997; Hsu et al. 1995; Wang et al. 2006) and postsynaptically opening potassium channels of Str projection neurons (Freedman and Weight 1988; Waszczak et al. 1998). Activation of D2LRs in Str can also disinhibit Str projection neurons by inhibiting fast firing GABAergic interneurons (Trevitt et al. 2005) and by decreasing GABA release from local collateral axons of striato-GPe projection neurons (Delgado et al. 2000). This study showed that the effects of D2LR activation that inhibit are stronger than those that disinhibit Str-GPe neurons.

Local application of quinpirole to the cortical stimulation site had no effect on the cortical stimulation-evoked IPSCs in GPe. This result may not be caused by a lack of quinpirole effects on cortico-Str neurons. Instead, we speculate that the

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**FIG. 5.** Application of quinpirole to the Str stimulus site reduced amplitudes of Str stimulation-evoked long latency IPSCs but not short-latency IPSCs in GPe neurons. A and C: summaries of the quinpirole effects on the amplitude of both long- and short-latency IPSCs observed during sequential application of 10, 20, and 50 μM quinpirole to Str for 5 min each. B and D: quinpirole did not alter paired pulse ratios of these responses. Paired t-test compared with control (\(*P < 0.05, **P < 0.01\)).

**FIG. 6.** Bath application of quinpirole reduced the frequency but not the amplitude of mIPSCs. mIPSCs with amplitudes exceeding 10 pA were recorded from GPe neurons with ACSF containing NBQX (10 μM), CPP (30 μM), and TTX (1 μM). A: sample traces of mIPSCs. B and C: frequencies and amplitudes of mIPSCs before and during application of 5–20 μM quinpirole. Quinpirole significantly diminished the frequencies but not the mean amplitudes of mIPSCs. The pretreatment of slices with 10 μM methysergide, a serotonin receptor antagonist, did not occlude 20 μM quinpirole effects on the frequency of mIPSCs (B). Paired t-test compared with control (\(*P < 0.05, **P < 0.01\)). D: cumulative amplitude distributions of mIPSCs recorded from a GPe neuron show no amplitude shift with 20 μM quinpirole (\(P > 0.05\), Kolmogorov-Smirnov test).

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result was caused by the placement of the stimulation electrodes. The cathode of the bipolar electrodes was located on the subcortical white matter and the anode on the deep layer of the cortex. This arrangement was suited for stimulating cortico-Str axons but not the somata or dendrites of cortical neurons.

**Effects of quinpirole on Str stimulation-evoked IPSCs in GPe**

Because of technical difficulties, we could not examine the effects of locally applied quinpirole to GPe recording sites with cortical stimulation-induced IPSCs. Instead, we examined the effects of local quinpirole application on Str stimulation-evoked IPSCs. Str stimulation at low intensity evoked ~8-ms latency IPSCs with <10-pA amplitude, and stimulation at high-intensity evoked ~5-ms-latency IPSCs with large amplitude in GPe neurons. Both IPSCs had a constant latency, followed double shock, and were completely blocked by application of 10 μM gabazine. We believe that the long-latency IPSCs were evoked mainly by Str-GPe axons and that the short-latency IPSCs were composed of an early component evoked by intrapallidal collateral axons of GPe-Str projection neurons (Kita 2007; Kita and Kitai 1994; Ogura and Kita 2000). Application of quinpirole to the GPe recording site decreased the amplitude of long-latency IPSCs and increased PPRs, suggesting that activation of D2LRs on Str-GPe axons decreased the probability of GABA release. Quinpirole also significantly decreased the amplitude of short-latency IPSCs with no significant change in their PPRs, suggesting that activation of D2LRs on intra-GPe collateral axons also suppressed GABA release. To confirm these possibilities, we examined effects of bath application of quinpirole on mIPSCs with the amplitude exceeding 10 pA. We confirmed that quinpirole decreased the frequency but not the amplitude or the amplitude distribution of mIPSCs. The serotonin antagonist methysergide, which blocked the presynaptic serotonin effects in rat GPe in vitro (Hashimoto and Kita 2008), did not occlude the quinpirole effect, suggesting quinpirole did not activate presynaptic serotonin receptors. The amplitude of IPSCs evoked by threshold cortical stimulation and threshold Str stimulation were <10 pA (also see Kita 2007). Thus most of the mIPSCs recorded in the recent study were likely to be evoked by intra-GPe collateral axons. These results indicated that activation of D2LRs suppresses GABA release from synaptic boutons of both Str-GPe and local collateral axons of GPe neurons projecting to Str.

**Other observations**

GPe neurons express D4 dopamine receptors (Ariano et al. 1997; Mauger et al. 1998), which increase potassium conductance and postsynaptically reduce GABAergic IPSCs in GPe neurons in mice (Shin et al. 2003). This study excluded the effects of D4 receptor activation because intracellular Cs ions and tetraethylammonium should largely block potassium currents of the neurons. Indeed, quinpirole application to bath or to GPe recording sites did not alter the input resistance of recorded neurons.

Washing slices for 15–20 min resulted in only partial recovery of the quinpirole effects. The slow recovery was probably caused by slow washout of quinpirole from the inside of the tissues because of the use of relatively high concentrations of quinpirole, relatively thick (400 μm) slices, and a slow flow rate (~2 ml/min of bath medium. Although the washout was slow, the sulphiride sensitivity suggested that the quinpirole effects observed in this study was D2 receptor mediated. A previous in vitro GPe study reported that the inhibition of evoked IPSCs or mIPSCs by 3 μM dopamine was only partially reversible, and the inhibition by >3 μM was irreversible (Cooper and Stanford 2001). They suggested the possibility that D2 receptor activation could evoke long-term changes downstream of receptor binding in GPe (Cooper and Stanford 2001).

**Functional considerations**

An increase in GPe firing activity was shown in some in vivo studies with systemic (Carlson et al. 1987; Hooper et al. 1997) or local (Bergstrom and Walters 1984; Querejeta et al. 2001) dopamine agonist application to GPe. The results were often interpreted as a presynaptic suppression of cortico-Str excitation or suppression of Str-GPe inhibition. The results of this study suggest that D2LR activation can suppress the gain of cortico-Str-GPe connection by suppressing both cortico-Str excitation and Str-GPe inhibition. Another role of D2LR activation in GPe may be feedback control of GPe activity through pre- and postsynaptic suppression of GPe-GPe inhibition.

The firing activity of GPe neurons in Parkinson’s disease patients and experimental parkinsonian animals increases in irregularity and bursting compared with controls (Beric et al. 1996; Filion and Tremblay 1991; Sterio et al. 1994; Wichmann and DeLong 2006). Increases in sensory responses such as the movement of multiple joints in GPe were also reported (Tremblay et al. 1989). These observations suggest that the gain of cortico-Str-GPe inputs is augmented in Parkinson’s disease subjects (Albin et al. 1989; Alexander and Crutcher 1990; DeLong 1990). The results of this study suggest that D2LRs control this disynaptic connection at both Str and GPe.

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