Pilocarpine-induced temporal lobe epilepsy in the rat is associated with increased dopamine neuron activity

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Abstract
Temporal lobe epilepsy (TLE) is defined as the occurrence of spontaneous seizures that involve the limbic system, with the hippocampal formation and associated structures being central to the most prevalent refractory form of adult focal epilepsy. TLE is often associated with psychotic features resembling the hallucinations and delusions that occur with schizophrenia. Given evidence that the ventral hippocampus plays an important role in the maintenance of temporal lobe seizures, we investigated whether an animal model of TLE using intrahippocampal injection of pilocarpine induces alterations in mesolimbic dopamine neuron activity. We found that in 60% of rats in which pilocarpine induced seizure activity, there was a significant increase in the number of dopamine neurons firing per electrode track. Furthermore, this occurred in concert with an increase in amphetamine-stimulated locomotor activity. Both observations are similar to those observed in a rodent developmental model of psychosis. Therefore, as in animal models of schizophrenia, TLE-associated psychosis is probably due to abnormal hippocampal overdrive of dopamine neuron activity.

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Introduction
The association between epilepsy and schizophrenia-like psychosis has attracted the attention of psychiatrists since the nineteenth century, but many aspects of this relationship remain controversial (Mendez et al. 1993; Qin et al. 2005; Trimble, 1991). Thus, there is a wide variation in the incidence of clinically significant psychiatric symptoms in individuals with epilepsy that depends strongly on the patient sample (Stevens, 1988). Moreover, several studies indicate that schizophrenia-like psychosis is 6–12 times more likely to occur in epileptic patients than in the general population (Slater et al. 1963).

Patients affected by temporal lobe epilepsy (TLE) often present symptoms such as aggressive irritability, humourless sobriety, circumstantial preoccupation with detail, nascent religious or philosophical interest, and altered sexual preference (Bear, 1979; Bear & Fedio, 1977; Waxman & Geschwind, 1974).

In addition, guilty rumination often leading to depression has been reported. Indeed, depression alone accounts for the most common comorbidity in patients with epilepsy (Harden, 2002; Kanner & Balabanov, 2002). Unfortunately, a consensus on the classification of psychotic syndromes associated with epilepsy is lacking, and neither DSM-IV nor ICD-10 has addressed this issue specifically.

Since clinical seizures are the outstanding feature of epilepsy, psychotic syndromes have traditionally been classified according to their temporal relationship to these events. Interestingly, the hippocampus plays a central role in the pathophysiology of both epilepsy (and particularly TLE) as well as schizophrenia. Thus, in addition to being among the lowest seizure threshold areas in the brain, substantial evidence has linked hippocampal pathology to schizophrenia, such as alterations in hippocampal morphology using magnetic resonance imaging (Lawrie & Abukmeil, 1998), reduced N-acetyl aspartate (Bertolino et al. 1996, 1998; Deicken et al. 1999; Maier et al. 1995), and the increased...
metabolism in the anterior hippocampus (Heckers, 2001; Tamminga et al. 1992) that correlates with psychotic symptoms (Silbersweig et al. 1995).

Animal models of schizophrenia have also implicated hippocampal pathophysiology as a driving force in the abnormal regulation of the dopamine (DA) system. Thus, in a developmental animal model of schizophrenia, a loss of parvalbumin interneuron staining in the hippocampus subiculum leads to an overdrive of the subiculum-nucleus accumbens pathway (Lodge et al. 2009). This, in turn, leads to an increase in DA neuron population activity, which is proposed to be the basis for DA system hyper-responsivity (Lodge & Grace, 2007). Thus, hyperactivity within the hippocampus leads to hyper-responsivity of the DA system, with DA hyper-responsivity proposed to underlie the psychotic symptoms of schizophrenia (Laruelle & Abi-Dargham, 1999). Indeed, as in this rodent model (Lodge & Grace, 2007), rats with pilocarpine-induced TLE also exhibit a substantially greater behavioural response to amphetamine (Ando et al. 2004).

Induction of TLE with pilocarpine is equally efficacious independent of whether the drug is administered systemically or intra-hippocampally (Furtado Mde et al. 2002), with the intra-hippocampal route associated with a markedly reduced mortality (Furtado Mde et al. 2002). With this method, approximately 70% of the animals are reported to experience status epilepticus (SE) within 30 min after intra-hippocampal infusion and present spontaneous recurrent seizures (SRSs) after a latent period of 2–30 d. Therefore, this model was used in the current study to examine the relationship between TLE and DA system function.

Material and methods

Animals

Adult male Sprague–Dawley rats (175–200 g) were obtained from Hilltop (USA) and housed in pairs on a 12-h light/dark cycle (lights on 07:00 hours), with food and water available ad libitum. All experiment were performed in accordance with the guidelines outlined in the National Institutes of Health Guide for the Care and Use of Laboratory Animals and were approved by the Institutional Animal Care and Use Committee of the University of Pittsburgh.

Surgery and pharmacological manipulation

Rats were anaesthetized with Nembutal and mounted on a stereotaxic frame using blunt atraumatic ear bars. A stainless-steel guide cannula was implanted in the right ventral hippocampus (vHipp) (AP − 6.0, ML +5.3, DV −4.5 mm from bregma) and fixed in place with dental cement and two or three anchor screws. Once the cement was completely solid, the wound was sutured, the rat removed from the stereotaxic apparatus and monitored closely until conscious. Rats received antibiotic treatment (gentamicin 3 mg/kg s.c.) and post-operative analgesia (Children’s Tylenol syrup in softened rat chow; 5% v/w) ad libitum for 24 h.

After 1 wk of recovery half of the total number of the animals that received cannula implants were infused intracranially into the vHipp with the proepileptic drug pilocarpine (Sigma, USA). Pilocarpine was dissolved in Dulbecco’s phosphate-buffered saline (PBS) and infused (2.4 mg/μl, 1 μl; duration ~30 s) through a 30-gauge injection cannula protruding 2.0 mm beyond the tip of the guide cannula. The remaining rats were infused with saline solution (0.9%, 1 μl).

Following the infusion of pilocarpine in the vHipp, the progressive evolution of seizures was observed and quantified using Racine’s motor scale (Racine, 2002). All motor activities were recorded using a digital camera. Animals exhibiting SE (defined as an epileptic seizure that lasts more than 30 min) were injected with diazepam (5 mg/kg i.p.) after 120 min of SE in order to stop seizure activity. SRSs appear in the animals infused with pilocarpine after a latent period of about 7–30 d. All rats were video monitored continuously after pilocarpine infusion (all during the SE period). After infusion the rats were video monitored to check for SRSs starting 1 wk after the infusion. This monitoring was made daily for 3 h per day (from 14:00 to 17:00 hours) since previous studies (Raedt et al. 2009) showed that seizures appear more frequently in this time-frame with a regular circadian rhythm. Only rats that displayed SRSs at least 2–3 times per day for a total of 1 wk after infusion of pilocarpine were used in this study. Before the electrophysiological and behavioural test animals were monitored by visual observation 2.3 h before the experiment to ensure that the recordings were not made in the immediate post-ictal period. Only animals that showed SE and SRSs were evaluated further.

Extracellular recordings

Only drug-naive animals were used for electrophysiological recordings to circumvent the effects of prior amphetamine exposure on DA neuron activity (Vanderschuren et al. 1999; Xia et al. 2008). Rats were used in the post-ictal period, with recordings made following the appearance of SRSs, which emerged on average at 2 wk post-injection and no observable seizures were present for at least 2.3 h prior to recording,
as described above. Animals were anaesthetized with 8% chloral hydrate (400 ml/kg i.p.) and mounted in a Kopf stereotaxic frame. Chloral hydrate was used since, with this drug, DA neuron activity states are consistent with those observed in freely moving rats (Hyland et al. 2002). Anaesthesia was maintained by supplementary administration of chloral hydrate as required to maintain suppression of the plantar reflex. Core body temperature was maintained at 37 °C using a thermostatically controlled heating pad.

A burr hole was drilled overlying the VTA (AP −5.1 to −5.5, ML +0.6 to +1, DV −6.5 to −8.5 mm from bregma), the dura was resected and glass extracellular microelectrodes (impedance 6–14 MΩ) were lowered into the region using a hydraulic microdrive (Kopf model 640). The activity of the population of DA neurons was obtained by counting the number of spontaneously active neurons encountered while making 6–9 vertical passes or tracks separated by 200 μm in a predetermined grid pattern throughout the ventral tegmental area (VTA). Spontaneously active DA neurons were identified using previously well-established electrophysiological criteria (Grace & Bunney, 1983) and once isolated their activity was recorded for 3 min.

Three parameters of activity were measured: (i) population activity (defined as the number of spontaneously active DA neurons recorded in each electrode track), (ii) basal firing rate, and (iii) the percentage of action potentials occurring in bursts (defined as the occurrence of two spikes with an interspike interval of >80 ms, and the termination of the burst defined as the occurrence of an interspike interval >160 ms (Grace & Bunney, 1984)). The data were acquired, stored and analysed using custom-designed computer software (Neuroscope, Brian Lowry, USA).

Amphetamine-induced locomotion

Behavioural data were collected following the emergence of SRSs, which appeared on average at 2 wk post-pilocarpine injection to correspond to the electrophysiological data, with video monitoring visually confirming the absence of an ictal state for a minimum of 2.3 h prior to the experiment. Epileptic rats and non-epileptic rats were placed in an open-field activity monitor (Coulbourn Instruments, USA) to automatically measure spontaneous locomotor activity in the x–y plane for 60 min by beam breaks and recorded with Truscan software (Coulbourn Instruments). Rats were then injected with d-amphetamine sulphate (1.5 mg/kg i.p.) and locomotor activity recorded for an additional 120 min. Only rats that displayed SRSs at least three times a day, for a total time of 1 wk after the infusion of pilocarpine in the vHipp, were used for this behavioural test.

Histology

At the cessation of the experiment, the recording site was marked via electrophoretic ejection of Pontamine Sky Blue dye from the tip of the recording electrode (30 mA constant current, 30–45 min). After dye injection, rats were killed by an overdose of chloral hydrate, decapitated and their brains removed, fixed for at least 48 h (8% w/v paraformaldehyde in PBS) and cryo-protected (25% w/v sucrose in PBS until saturated). Brains were sectioned (60 μm coronal sections), mounted onto gelatin-chrom alum-coated slides and stained with Cresyl Violet for histochemical verification of electrode sites and thionin for verification of cannula sites. All histology was performed with reference to the stereotaxic atlas of Paxinos & Watson (1986).

Analysis

Electrophysiological analysis of DA neuron activity was performed using custom-designed computer software (Neuroscope), and locomotor behaviour was recorded using TruScan software (Coulbourne Instruments). All data are presented as mean ± S.E.M. unless otherwise stated. All statistics were calculated using the GraphPad Prism software (GraphPad Software Inc., USA) for Student’s t test for electrophysiological data and SigmaPlot 11 (Systat Software, Inc., USA) for repeated-measures ANOVA for the locomotor data.

Results

Of a total of 50 animals infused in the vHipp with pilocarpine, one did not show seizure activity, whereas 49 experienced epileptic seizures. The distribution along the Racine motor scale is summarized in Fig. 1. Animals in stage 1 (n = 4) were not used, since it was difficult to discriminate between a stage 1 seizure and the normal movements of the head and mouth in these animals. Of the remaining 45 animals, 15 were used for the electrophysiological recordings and 16 were used for amphetamine-induced locomotor activity. Of the 14 remaining animals, eight had misplaced lesion sites and six failed to show SRSs for at least 2–3 times per day, and were excluded from further analyses.

VHipp infusion of pilocarpine increases VTA DA neuron activity

Animals that received saline infusion in the vHipp (n = 14 rats, 114 neurons) exhibited an average of 0.85 ± 0.24 spontaneously active DA neurons per
electrode track, with an average firing rate of 5.18±2.04 Hz and with 43.0±15.2% of action potentials fired in bursts, which is consistent with previous findings in untreated rats (Floresco et al. 2003; Lodge & Grace, 2006a, b). Approximately 60% (9/15) of the rats infused with pilocarpine into the vHipp and exhibiting seizure activity between II and V on the Racine scale (n = 9 rats, 90 neurons) showed significantly greater DA neuron population activity and were labelled as responders (1.62±0.29 cells/track, t = 7.018, p < 0.001), and showed small but significant reductions in average burst firing (29.8±11.6%, t = 2.453, d.f. = 22, p < 0.05) relative to controls (Fig. 2). However, when examined, it was clear that nearly 40% (6/15) of the rats tested exhibited DA neuron population activity nearly identical to that of controls (0.82±0.08 cells/track, 4.4±1.75 Hz, 38.3±13.4% of bursting cells). These rats were defined as non-responders if their cells/track was <1.1; the resultant group mean for these animals fell within a 5% confidence interval (CI) of the control rats (control 5% CI 0.71–0.99 cells/track) but not for the responders. These groups of rats showed clear separation in DA neuron activity (Fig. 2). There was no correlation between the severity of the epileptic scores with the response status. Such an observation is consistent with what would be predicted from the clinical literature regarding TLE, in that only 6–12% of patients with TLE exhibit psychosis. Since in our experimental protocol we made a well-controlled lesion, we expected greater consistency in the impact on the DA system.

**TLE rats exhibit increased behavioural response to amphetamine injection**

Previous studies in the gestational methyazox methanol (MAM) developmental model of schizophrenia and with amphetamine sensitization (Lodge & Grace, 2007) demonstrated that hyperactivity in the hippocampus is responsible for the increased baseline DA

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**Fig. 1.** Distribution of the animals (n=49) infused with pilocarpine according to Racine’s motor scale of epilepsy, with I being mild seizure activity (i.e. mouth and facial movement) and V representing the strongest form of seizure (rearing and falling with forelimb clonus). Only rats scoring II–V were used in the study.

**Fig. 2.** Effect of intrahippocampal (i.h.) pilocarpine infusion (2.4 mg/ml) on ventral tegmental area dopamine (DA) neuron population activity. DA neuron population activity was examined when spontaneous recurrent seizures appear, which was typically at least 2 wk following i.h. infusion of pilocarpine (Pilo). Rats examined electrophysiologically (n = 15 Pilo, n = 14 controls) were divided into two groups: Pilo responders (n = 9) and Pilo non-responders (n = 6). The non-responders showed values of cells/track that were within a 5% confidence interval of controls. The Pilo responders showed a significant increase in DA neuron population activity (c; t test, *** p < 0.001) with small but significant decreases (b) in the average percent of burst firing (* p < 0.05), but not in (a) firing rate.
neuron population activity that correlated with behavioural hyper-responsivity to amphetamine injection (Lodge & Grace, 2008). Given evidence of the role of the hippocampus in the regulation of DA neuron population activity, the behavioural responsivity to amphetamine was examined in this model of epilepsy.

Consistent with these previous observations, the pilocarpine-infused rats ($n = 16$) exhibited significantly enhanced locomotor response to d-amphetamine administration compared to rats infused with saline solution ($n = 16$; repeated-measures ANOVA group × time interaction: $F = 7.742$, d.f. = 35, $p < 0.001$; Fig. 3). This increase in distance travelled is 75% higher than in controls, and this increase reached maximum approximately 25–30 min after the amphetamine injection. After almost 2 h following the amphetamine injection, the pilocarpine-injected rats recovered to the baseline level of movement observed before the amphetamine injection. Taken together, these data suggest that in pilocarpine-treated rats a pathologically increased DA neuron population activity and the related increased responsivity to amphetamine administration are probably attributable to hippocampal hyperactivity.

**Discussion**

The data presented here demonstrate, for the first time, that pilocarpine-treated rats display an abnormally enhanced DA neuron drive in the form of an increase in DA neuron population activity. Specifically, we demonstrated that most of the pilocarpine-treated rats display a significantly higher number of spontaneously firing DA neurons compared to control rats. Our studies show that DA neuron population activity, defined as the proportion of spontaneously firing DA neurons, is regulated in normal rats by a ventral subicular-nucleus accumbens-ventral pallidal-VTA pathway (Floresco et al. 2003). Therefore, a TLE-associated pathological hyperactivity in the hippocampus should in turn lead to increased VTA DA neuron activity. Since DA neurons must be spontaneously active in order to exhibit phasic burst firing responses to inputs (Lodge & Grace, 2006), abnormally high levels of population activity would enable a phasic burst stimulus to elicit burst firing in a greater number of DA neurons, thereby putting the DA system in a hyper-responsive state. Indeed, hippocampal hyperactivity has been linked to psychosis in a rat developmental model of schizophrenia (Lodge & Grace, 2006a, 2008) which, similar to that observed in patients (Laruelle & Abi-Dargham, 1999), is characterized by hyper-responsivity of the DA system to amphetamine.

Therefore, the link between hippocampal hyperactivity and DA dysregulation leading to psychosis may be a common pathophysiological variable across several disease states. Although there was an increase in population activity in the pilocarpine-responsive rats, there was no change in the average firing rate and only a small decrease in percent burst firing, consistent with our previous studies (Lodge & Grace, 2006a, 2008). As suggested in this previous study, this is probably due to recruitment of slowly firing, non-bursting neurons that, when averaged across the population of activated neurons did not result in a substantial difference in rate or pattern.

The source of the hippocampal hyperactivity and resultant DA neuron drive in TLE is not known. Wozny et al. (2005) suggested that the increased excitability is associated with a pronounced neurodegeneration in layer III of the medial enthorinal cortex (mEC) in patients and in models of temporal lobe epilepsy. In fact the EC seems to be critically involved in TLE. This limbic region shows an enhanced susceptibility to seizures and epileptiform discharge (Collins et al. 1983; Dasheiff & McNamara, 1982; Spencer & Spencer, 1994). Previous studies showed that SE causes a preferential loss of glutamatergic neurons while sparing GABAergic neurons in layer III of the mEC (Du et al. 1995; Eid et al. 1999; Kobayashi et al. 2003). Interestingly the projection that originates from

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**Fig. 3.** Consistent with a previous study in which DA neuron activity was assessed in an animal model of schizophrenia, pilocarpine-treated rats ($n = 16$) displayed a hyperdopaminergic condition reflected by a significant enhancement in locomotor response (repeated-measures ANOVA, $p < 0.001$) following administration of 1.5 mg/kg d-amphetamine (arrow represents the injection of amphetamine) compared to controls ($n = 16$). Taken as a whole these data suggest that in pilocarpine-treated rats a pathologically increased DA neuron population activity is associated with increased responsivity to amphetamine.
cells in layer III, the so-called temporoammonic pathway, terminates exclusively in CA1 and the subiculum (Amaral & Witter, 1989; Witter et al. 1989).

In contrast, Knopp et al. (2005) suggested that the vulnerability of the subicular GABAergic interneurons causes an input-specific disturbance of the subicular inhibitory system. They showed that in the subiculum of pilocarpine-treated animals the density of glutamic acid decarboxylase (GAD) mRNA-positive cells was reduced in all layers. Furthermore, they showed a substantial loss of parvalbumin-immunoreactive neurons in pyramidal cells and in the molecular layer. Interestingly we found a similar pattern of parvalbumin-containing interneuron loss in an animal model of schizophrenia (Lodge et al. 2009), which is a robust finding reported in schizophrenia brains post-mortem (Lewis et al. 2008). This deficit in the intrinsic GABAergic signalling may be the origin of the hippocampal hyperactivity that seems to underlie the DA dysfunction in psychosis in both TLE and schizophrenia.

These electrophysiological findings are supported by results obtained with the locomotor test activity performed after injection of the psychostimulant d-amphetamine, a well-validated animal model of psychosis. In fact we demonstrate a marked potentiating effect of stimulant-induced locomotor hyperactivity in pilocarpine-treated rats in accordance with previous studies made in both pilocarpine models and other models of experimental epilepsy (Ando et al. 2004; Jones et al. 2010; Ma & Leung, 2004; Muller et al. 2009; Szyndler et al. 2005). The fact that the use of a cholinergic drug reproduced aspects of TLE seen with other models suggests that it is the epileptogenic properties of the drug, rather than its cholinergic properties, that were significant in this model. Given that the primary mechanism of action of psychostimulants is to increase extracellular DA, this behavioural sensitization is attributable, at least in part, to enhanced activity of the mesolimbic DA pathway (Lodge & Grace, 2008; Pierce & Kalivas, 1997; White & Wang, 1984). Interestingly, in contrast to the electrophysiological results, all pilocarpine-treated rats tested for amphetamine-induced locomotor activity exhibited a heightened response. While the source of this difference is not known, one possibility could be due to the anti-epileptic effects of the anaesthetic, causing a proportion of rats to exhibit attenuated hippocampal hyperactivity.

Taken as a whole, the present study demonstrates that the increased responsivity to psychostimulants observed in pilocarpine-treated rats is probably attributable to an increase in tonic DA transmission secondary to augmented activity within the vHipp. This augmentation of vHipp drive was also found in an animal developmental model of schizophrenia in which endogenous vHipp overdrive also leads to aberrant DA signalling (Lodge & Grace, 2007). One difficulty associated with psychosis in TLE is its resistance to treatment (Chakir et al. 2006; Glien et al. 2002). By understanding the pathological alterations in the DA system induced by TLE, we will be in a better position to design effective therapeutic interventions that can address the dysfunction at the source of DA overdrive, rather than blocking the post-synaptic consequences of the hyperdopaminergic condition.

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Statement of Interest

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