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Decreased Dopamine D4 Receptor Expression Increases Extracellular Glutamate and Alters Its Regulation in Mouse Striatum

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Abstract

To better understand the effect of the dopamine D4 receptor (DRD4) on glutamate (Glu) neurotransmission in the brain, we utilized transgenic mice with partial or complete removal of functional DRD4 plasma membrane expression (DRD4^{+/-} and DRD4^{-/-}, respectively). We measured resting extracellular Glu levels, Glu clearance kinetics, and KCl-evoked release of Glu in the striatum and nucleus accumbens core of these mice using *in vivo* amperometry coupled to a novel microelectrode array configured for sub-second detection of Glu. Recordings from DRD4^{-/-} and DRD4^{+/-} mice were compared with their wild-type littermates (DRD4^{+/+}). Resting extracellular levels of Glu were increased in the striatum of DRD4^{-/-} mice ($p < 0.01$). Glu clearance kinetics were significantly decreased in the dorsal striatum of DRD4^{-/-} mice ($p < 0.05$). KCl-evoked overflow of Glu was reliably measured but unchanged in the striatum of the three groups. By contrast, no changes in resting Glu, Glu uptake kinetics, or KCl-evoked release of Glu were observed in the nucleus accumbens core among the three genotypes. These data indicate that

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DISCLOSURE/CONFLICT OF INTEREST

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the DRD4 receptor is involved in modulation of Glu neurotransmission, primarily in the striatum. A better understanding of Glu control by the DRD4 may improve our understanding of the physiological role of the DRD4 in disorders such as attention-deficit/hyperactivity disorder and schizophrenia.

Keywords

dopamine D4 receptor; glutamate; striatum; nucleus accumbens; amperometry; attention-deficit/hyperactivity disorder (ADHD)

INTRODUCTION

The dopamine (DA) D4 receptor (DRD4) is part of the DA D2-like receptor subfamily (Jaber et al, 1996; Grady et al, 2003; Lichter et al, 1993; Cooper et al, 2003). On binding DA, this G-protein-coupled receptor undergoes a conformational change activating the inhibitory α -subunit that interacts with signaling mechanisms resulting in several downstream signaling events including (but not limited to) inhibition of adenylate cyclase, stimulation of arachidonic acid release, and modulation of G-protein-regulated inwardly rectifying potassium channels (Jaber et al, 1996; Tarazi et al, 2004; Oak et al, 2000). At a behavioral level, it has been shown that DRD4 plays a role in novelty seeking, hyperactivity, and impaired behavioral inhibition in rodents, nonhuman primates, and humans (Ebstein et al, 1996; Avale et al, 2004; Zhang et al, 2001, 2002; Benjamin et al, 1996). Meta-analysis has indicated a higher frequency of a seven-repeat polymorphism in the D4 receptor in patients and relatives with attention-deficit/hyperactivity disorder (ADHD). Additionally, DRD4 alleles have been variously implicated in schizophrenia, perfectionism, migraine severity, and smoking (Bachner-Melman et al, 2007; de Sousa et al, 2007; Seeman et al, 1993; Guo and Tong, 2006).

The DRD4 is primarily expressed on pyramidal neurons and interneurons in the prefrontal cortex, but there is also support for DRD4 localization on medium spiny neurons in the basal ganglia (striatum, Str; and nucleus accumbens core, NAc), throughout the limbic system and in the thalamus of rodents (Mrzljak et al, 1996; Ariano et al, 1997a, 1997b; Tarazi et al, 2004; Gan et al, 2004; Cooper et al, 2003). In a study by Rivera et al (2002), DRD4s were found to be in higher concentrations in the densely packed neuron bundles, known as striosomes, of the Str in comparison with the more background neurons known as matrix. The striosomes receive input from limbic areas, cingulate cortex, and thalamus, indicating a role for DRD4 in regulation of the cortico-striatal-thalamic loop (Rivera et al, 2002). Three of the five proposed partially closed corticostriatal-thalamic circuits are predicted to be associated with ADHD (Sagvolden et al, 2005; Alexander et al, 1986); therefore, it is possible to speculate that DRD4s may modulate part of this circuitry and lead to some of the behaviors in ADHD. Glutamate (Glu) is the main neurotransmitter for multiple connections in this circuit; therefore, understanding direct and indirect glutamatergic modulation in an *in vivo* setting will be essential in working out the pathophysiology of multiple brain disorders.

Until now, it has been difficult to study the neurochemical effects of DRD4s, because commercially available ligands for the DRD4 are nonspecific (Hai-Bin et al, 2005; Defagot

et al, 2000). An alternative approach is to use wild-type (DRD4+/+), heterozygous (DRD4+/-), and knockout (DRD4-/-) mice for these studies (Rubinstein et al, 1997). Using biotinylation and western blotting, Rubinstein et al (1997) showed that there was no expression of the DRD4 in DRD4-/- mice and a 50% reduction of DRD4 expression in the DRD4+/- mice. Rubinstein et al (2001) presented evidence that the DRD4-/- mice exhibit cortical hyperexcitability using immunohistochemical, electrophysiological, pharmacological, and ultrastructural methods. Their results were consistent with the interpretation that DRD4 activation in DRD4+/+ mice has an inhibitory influence on Glu-containing pyramidal neurons in the frontal cortex (Rubinstein et al, 2001). With the lack of inhibitory modulation as a result of no functional DRD4s in the prefrontal cortex of DRD4-/- mice, we would expect decreased inhibition of glutamatergic pyramidal neuron firing. This would result in increased firing of Glu-containing neurons, and, thus, changes in Glu neurotransmission in the Str and NAc. At this time, no direct studies of resting extracellular Glu, Glu clearance, and evoked Glu release have been investigated in these animals.

In a recent study, we demonstrated that DRD4-/- mice have reduced levels of resting extracellular DA and decreased potassium (KCl)-evoked DA in the Str and NAc (Thomas et al, 2007). The purpose of the present studies was to further characterize the DRD4-/- mice with respect to Glu neurotransmission in these areas. First, we characterized resting extracellular levels of Glu in the Str and NAc of DRD4+/+, DRD4+/-, and DRD4-/- mice. Second, we characterized Glu clearance by local application of exogenous Glu in the three animal groups. Third, we characterized KCl-evoked Glu in the Str and NAc of these animals. We hypothesized that DRD4 mice would show evidence of a hyperglutamatergic state.

MATERIALS AND METHODS

Animals

Male mice (5–7 months) descended from the original F₂ hybrid of mice with a truncated and non-expressing DRD4 gene (DRD4-/-) (129/SvEv × C57BL/6J; Rubinstein et al, 1997) were derived by backcrossing the heterozygous (DRD4+/-) mouse line for 20 generations (N20). In all experiments, the DRD4-/- mice ($n = 7-9$) and DRD4+/- ($n = 6-8$) were compared with litter-matched DRD4+/+ ($n = 7-9$) animals. Mice were group-housed (2–4 per cage) with unlimited access to food and water. Mice were maintained on a 12-h light/dark cycle (lights on at 0600 hours). Protocols for animal use were approved by the Institutional Animal Care and Use Committee, which is Association for Assessment and Accreditation of Laboratory Animal Care International approved. All procedures were carried out in accordance with the National Institutes of Health Guide for Care and Use of Laboratory Animals.

Microelectrode Array Preparation and *In Vitro* Calibrations

Microelectrode preparation for Glu recordings.—Ceramic-based microelectrode arrays (MEAs) that contained four platinum (Pt) recording surfaces were prepared to selectively measure Glu (Figure 1a). These electrodes were fabricated for *in vivo* recordings using published methods (Burmeister et al, 2000, 2002; Nickell et al, 2005). All four sites

were electroplated with meta-phenylenediamine (mPD) by applying a potential of +0.5 V to the Pt sites *vs* a silver/silver chloride (Ag/AgCl) reference electrode (Bioanalytical Systems, RE-5) in a deoxygenated 0.05 M phosphate-buffered saline (PBS, pH 7.1–7.4) with 5.0 mM mPD. The mPD forms a size-exclusion layer over the sites, blocking DA, ascorbic acid (AA), DOPAC, and other electroactive compounds. Pt sites 1 and 2 (see Figure 1a) were then coated with glutamate oxidase (Glu-Ox) within an inert protein matrix of bovine serum albumin (BSA) and glutaraldehyde (Glut), enabling these sites to detect Glu levels on a sub-second timescale with low levels of detection (~0.2 μ M). Sites 3 and 4 were coated with only BSA and Glut (Burmeister and Gerhardt, 2001; Day et al, 2006). In the presence of Glu-Ox, Glu was broken down into α -ketoglutarate and peroxide (H_2O_2). The H_2O_2 is small enough to traverse the mPD layer and was readily oxidized and recorded as current using FAST-16 equipment (Fast Analytical Sensor Technology (FAST); Quanteon LLC, Nicholasville, KY).

Microelectrode calibration.—The microelectrode was submerged in 40 ml of 0.05 M PBS (pH 7.1–7.4) warmed to 37°C using a circulating water bath (Gaymar Industries Inc., Orchard Park, NY), and stirred using a magnetic stir bar and battery operated stir plate (Barnart Co.). Measurements were made using an applied potential of +0.7 V *vs* an Ag/AgCl reference electrode (Bioanalytical Systems; RE-5). Signals were amplified by the headstage gain (2 nA/V) and a secondary gain of 10 times for a final gain of 200 pA/V. Following a 10- to 20-min equilibration, aliquots of stock solutions were added to the PBS (see Figure 1b). The final concentrations of the stock solutions in the 40-ml PBS were 250 μ M AA; 20, 40, and 60 μ M L-glutamate (L-Glu); 2 and 4 μ M DA; and 8.8 μ M H_2O_2 . AA and DA were used to ensure that the mPD coating was blocking these electroactive molecules that are abundant within the Str and NAc. From the calibration, the slope (electrodes sensitivity to L-Glu), selectivity (capabilities of recording L-Glu over AA), and limit of detection (LOD—smallest amount of detectable Glu) were calculated: average values for slope were -7.5 ± 5.0 pA/ μ M, for selectivity were 214 ± 48 to 1, and for LOD were 0.72 ± 0.12 μ M ($n = 28$ electrodes; 56 Glu recording sites).

Micropipette attachment.—After the MEA was calibrated, a single barrel glass capillary with filament (1.0×0.58 mm², 6"; A-M Systems Inc., Everett, WA) was pulled using a Kopf pipette puller (David Kopf Instruments, Tujunga, CA) and bumped for an inner diameter of 10–12 μ m. The tip of the micropipette was placed between the four recording sites, approximately 50–80 μ m away from the electrode surface and secured using Sticky Wax (Kerr Manufacturing Co., Detroit, MI). For these studies, the average distance was approximately 65 μ m.

Surgeries for Amperometric Recordings

Mice were anesthetized using intraperitoneal injections of 10% urethane solution (1.25 g/kg) and placed in a stereotaxic frame (David Kopf Instruments) fitted with a Cunningham™ Mouse and Neonatal Rat Adaptor (Stoelting Co., Wood Dale, IL). A circulating heating pad (Gaymar Industries Inc.) coupled to a rectal temperature probe (Yellow Spring Instrument Co., Yellow Springs, OH) was used to maintain body temperature at 37°C. The skull overlying the medial cortex was removed bilaterally. An additional hole, remote from the surgery site, was opened for an Ag/AgCl reference electrode (Hascup et al, 2006).

In Vivo Experimental Protocol

Prior to placement of the MEA micropipette assembly, the micropipette was filled with isotonic 125 μM Glu (125 μM L-Glu in 9% physiological saline; pH 7.2–7.4) or 35 mM KCl solution (35 mM KCl, 114 mM NaCl, 2.5 mM CaCl_2 ; pH 7.2–7.4) using a combination of a 1-ml syringe filled with Glu or KCl solutions, a 0.22- μm sterile syringe filter (Costar Corporation), and a 4" pulled needle (30 gauge, beveled tip; Popper and Son Inc., NY). The MEA micropipette assembly was positioned in the brain according to the following stereotaxic coordinates where all anterior–posterior (AP) measures were from bregma, medial–lateral (ML) measures were from midline, and dorsal–ventral (DV) measures were from dura: AP: + 1.1 mm, ML: \pm 1.1 mm, DV: –2.25–4.1 mm; and AP: + 1.4 mm, ML: \pm 1.4 mm, DV: –2.25–4.1 mm according to the Mouse Brain in Stereotaxic Coordinates (see Figure 1d; Franklin and Paxinos, 1997). A potential of + 0.7 V was applied *vs* a miniature Ag/AgCl reference electrode, and the data were displayed at a frequency of 2 Hz. Recordings made at depths of 2.15, 2.5, and 2.85 mm were used for measures in the dorsomedial Str and recordings at 3.65 and 4.0 mm were used for measures in the NAc (see Figure 1c).

Nanoliter volumes of Glu or KCl were locally applied to tissue by pressure ejection using a Picospritzer II connected to the open end of the micropipette by plastic tubing (Parker Hannifin Corp., General Valve Corporation). Pressure was applied at 5–25 p.s.i. for 1 s in all of the experiments. The volume of Glu or KCl delivered was measured by determining the amount of fluid ejected from the micropipette using a dissection microscope fitted with a calibrated reticule (Cass et al, 1992; Friedemann and Gerhardt, 1992).

Measurements of resting levels and Glu clearance parameters.—Upon stereotaxic placement of the MEA micropipette assembly (AP: + 1.1 mm, ML: \pm 1.1 mm, DV: –2.15–4.0 mm), 10–20 min of baseline data were acquired. Resting levels of Glu were measured by averaging 30 s of baseline recordings prior to application of Glu or KCl. Then, 125 μM Glu solution was locally applied every 30–60 s for a total of 10 recordings. The MEA was then lowered in 350 μm increments. Baseline recordings were acquired for 5–10 min and the recordings were repeated. Parameters from 3 of the 10 signals ranging from 10–30 μM in amplitude were averaged for each Pt electrode site at each depth. The calculations from the left and right hemispheres were averaged for a single measurement per depth in all mice. Signals were analyzed for time required to rise to maximum amplitude (rise time), time for 80% of the signal to decay from maximum amplitude (T_{80}), and the rate of uptake (see Figure 1d). The uptake rate was calculated by multiplying the rate constant (referred to as k_{-1} ; units = per seconds) by the maximum amplitude (uptake rate = $\mu\text{M}/\text{s}$; Hascup et al, 2006). All data from local applications of Glu were pooled into a single data set. Amplitude-matched signals were compared with assess genotypic differences in the rates of clearance of exogenous Glu. Volume-matched signals were compared to determine capacity to clear similar amounts of exogenous Glu (Hebert and Gerhardt, 1999).

KCl-induced release of Glu.—KCl was locally applied by pressure ejection into the Str and NAc (AP: + 1.4 mm, ML: \pm 1.4 mm, DV: –2.0–4.1 mm) (Franklin and Paxinos, 1997), once a steady-state signal was achieved, the effects of a single local application of KCl

solution on Glu release were determined (Gerhardt et al, 1985, 1986, 1987; Gerhardt and Palmer, 1987; Luthman et al, 1993; Cass et al, 1993). Data regarding amperometric recordings were volume matched (12.5–100 nl) prior to data analysis. Recordings from sites 1 and 2 were averaged, and data from both hemispheres were averaged to one data point per depth.

Materials

Urethane, L-Glu, DA, AA, sodium chloride, potassium chloride, calcium chloride, and 1,3-phenylenediamine dihydrochloride were obtained from Sigma (St Louis, MO). MEAs were provided by Quanteon LLC and constructed in conjunction with Thin Films Technology Inc. (Buellton, CA).

Histology

Brains were removed and processed for histological evaluation of microelectrode recording tracts. Only data from histologically confirmed placements of microelectrodes within the Str and NAc were used for final data analysis.

Data Analysis

Data from the side-by-side recordings were averaged and used as a single data point. If only one electrode site provided usable data, then the recordings were reported as from that site. No outliers were removed from the presented data, but some data were excluded due to volume or amplitude-matching criterion. To determine statistical significance ($p < 0.05$) processed data were analyzed using a one-way ANOVA with Tukey's *post hoc* comparison across all genotypes (Graphpad Prism 4.0).

RESULTS

Resting Levels of Extracellular Glu in the Str and NAc

To evaluate the effect of DRD4 expression level on resting levels of Glu, we compared extracellular Glu levels across genotypes in the Str and NAc (see Figure 2). Resting levels of Glu were seen to be increased by 64% in the Str of DRD4^{-/-} mice in comparison with their wild-type littermates (DRD4^{+/+}: $1.5 \pm 0.3 \mu\text{M}$, $n = 7$; signals = 45; DRD4^{-/-}: $2.4 \pm 0.2 \mu\text{M}$, $n = 9$, signals = 45; $p < 0.01$; see Figure 2). There were no significant changes in the NAc, although there was a trend for slightly higher Glu levels in the DRD4^{-/-} mice (DRD4^{+/+}: $1.3 \pm 0.2 \mu\text{M}$; DRD4^{-/-}: $1.8 \pm 0.2 \mu\text{M}$; $p < 0.10$). The DRD4^{+/-} mice were most similar to the DRD4^{+/+} mice in both the Str and NAc (Str: $1.4 \pm 0.2 \mu\text{M}$, $n = 7$; signals = 35; NAc: $1.2 \pm 0.2 \mu\text{M}$, $n = 6$; signals = 22). These data indicate that the loss of DRD4 expression resulted in increased resting Glu levels in the Str.

Glu Clearance in the Str and NAc

The *in vivo* activity of Glu uptake was examined with a high degree of temporal and spatial resolution by locally applying exogenous Glu to the tissue and measuring the presence and successive clearance kinetics of the signals (Cass et al, 1993). Resulting data provided kinetic measures that allowed us to evaluate removal of exogenous Glu from the

extracellular space within the Str and NAc. Statistical comparisons were made on amplitude-matched data to make sure that variations in maximum amplitude would not contribute to changes in rise time, uptake rate, and T_{80} . In the Str, average amplitudes were $20.0 \pm 0.8 \mu\text{M}$ ($n = 8$; signals = 24), $19.5 \pm 1.2 \mu\text{M}$ ($n = 8$; signals = 23), and $18.9 \pm 1.0 \mu\text{M}$ ($n = 9$; signals = 26) in the DRD4+/+, DRD4+/-, and DRD4-/- mice, respectively. The locally applied Glu signals took approximately 1–2 s to rise to maximum amplitude (rise time). Rise time did not vary significantly between genotypes in the Str or the NAc. Uptake rate in the Str was significantly slower in the DRD4-/- mice in comparison with DRD4+/+ mice (5.3 ± 0.5 vs $7.4 \pm 0.6 \mu\text{M/s}$; $p < 0.05$; see Figure 3a and c). The slower uptake rate of Glu from the extracellular space is supported by a trend of increased time taken for 80% of the Glu to decay from the recording site (T_{80} ; DRD4+/+ : 3.2 ± 0.2 s vs DRD4-/-: 4.4 ± 0.5 s; Figure 3). Kinetic measures of Glu clearance in the NAc showed no significant differences among genotypes (Figure 3b). Thus, we concluded that only the uptake rate was decreased in the Str of the DRD4-/- mice.

To investigate genotype-related changes in the Str and the capacity of NAc to clear exogenous Glu (Cass and Gerhardt, 1995), similar amounts of exogenous Glu were locally applied to the different genotypes, and the resulting maximum amplitudes and amplitudes per nanoliter were compared. Signal amplitude and normalized amplitude per nanoliter measures within the Str and NAc of DRD4+/+, DRD4+/-, and DRD4-/- mice are presented in Table 1. There were no significant differences between genotypes in the Str or NAc, although a trend for higher levels of Glu per nanoliter were seen in the DRD4+/+ mice in both brain regions. Thus, there is likely similar surface expression of Glu transporters in the different genotypes.

KCI-Evoked Glu Release in the Str and NAc

To evaluate the effect of the DRD4 on synaptic release of Glu and to assess biologically relevant levels of evoked Glu release, we locally applied similar amounts of KCl to the Str and NAc of DRD4+/+, DRD4+/-, and DRD4-/- mice. Figure 4 depicts representative traces of KCl-evoked Glu signals in the three genotypes of mice from the Str. There were no significant differences in the amount of KCl-evoked Glu release, although there was a trend for higher amounts of KCl-evoked Glu overflow in the Str and NAc of the DRD4+/+ mice (see Table 2). The temporal properties of the signals were also not significantly different between the three groups of mice in the Str and NAc. Interestingly, the rise times for KCl-evoked Glu in the Str averaged 1.6 ± 0.1 s for the DRD4-/- mice, 1.4 ± 0.1 s for the DRD4+/- mice, and 1.2 ± 0.1 s for the DRD4+/+ mice. We also measured T_{80} in the three genotypes and found that these averaged 3.7 ± 0.2 s for the DRD4-/- mice, 3.6 ± 0.3 s for the DRD4+/- mice, and 3.4 ± 0.4 s for the DRD4+/+ mice in the Str. Similar rise times and T_{80} values were seen in the NAc (data not shown). Thus, although KCl produced robust changes in extracellular Glu, no significant differences were observed in the Str and NAc due to alterations in D4 expression.

DISCUSSION

We sought to understand the DRD4s involvement in Glu regulation in the Str and NAc of DRD4^{+/+}, DRD4^{+/-}, and DRD4^{-/-} mice. *In vivo* amperometric studies showed a 64% increase in resting Glu levels in the Str of DRD4^{-/-} mice. In addition, Glu clearance was significantly slower in the Str of DRD4^{-/-} mice. Interestingly, these changes were not seen in the NAc. No statistically significant differences were observed in volume-matched Glu clearance studies or KCl-evoked Glu release in Str and NAc. No significant alterations were measured in the heterozygous mice indicating that greater than 50% loss of DRD4s is needed to measure the effects on Glu neurotransmission. Taken together, these data indicate a possible role for the DRD4 in the regulation of Glu in striatal circuitry.

Analyses of resting extracellular Glu levels in the past were often done by various forms of microdialysis (Espey et al, 1998; Behrens et al, 2002). This is the first study we know of looking at resting Glu levels in the Str and NAc of anesthetized C57BL/6J mice using a microelectrode technology. Espey et al (1998) reported levels at $0.9 \pm 0.1 \mu\text{M}$ in anesthetized C57BL/6J background mice using microdialysis. Behrens et al (2002) reported baseline levels of $0.7 \pm 0.1 \mu\text{M}$ in the Str of freely moving mice using microdialysis. Our microelectrode data showed striatal extracellular Glu levels of $1.5 \pm 0.2 \mu\text{M}$, almost twice that of the microdialysis studies. Variations in the resting Glu levels as recorded by *in vivo* amperometry and microdialysis may be multifactorial, including the different sizes of the probes and the temporal resolution of the measures. The MEA is much smaller than the microdialysis probe, producing less cellular damage and likely recording much closer to intact synapses (Rutherford et al, 2007). In anesthetized animal studies, microdialysis shows evidence of tissue disruption of at least 220–250 μm away from the probe (Borland et al, 2005), whereas the MEA showed evidence of some neuroinflammation only 50–100 μm away in a chronic study following 8 weeks *in vivo* (Rutherford et al, 2007). The temporal resolution of our MEA is an order of magnitude faster than the most sophisticated microdialysis techniques designed for measurement of amino-acid neurotransmitters (Kennedy et al, 2002).

The microelectrode technology also has the advantage of being able to measure Glu clearance kinetics. Different uptake rates across genotypes indicate significant DRD4-related alterations in the duration of Glu in the extracellular space, which likely denotes the importance of the DRD4 in regulating Glu clearance. Glu was cleared approximately 29% slower in the Str of DRD4^{-/-} mice as compared with DRD4^{+/+} animals. It is not known whether the measured effects on uptake rate were a direct or indirect effect of DRD4 signaling loss. Although it is unlikely that a resting Glu concentration of $2.4 \mu\text{M}$ is saturating uptake sites, it is possible that the increased extracellular Glu levels interact with glial Glu receptors to affect Glu transport. Within the NAc, the uptake rate did not change as a function of the presence of the DRD4. Volume-matched clearance of exogenous Glu data also showed no significant changes in maximum amplitude. Another possible consequence of a slower Glu uptake rate could be that Glu remains in the extracellular space longer, resulting in altered postsynaptic signaling in the DRD4^{-/-} mice.

Another parameter of the Glu clearance system is B_{\max} , or the surface expression of Glu transporters located on glia and neurons. Previous research in our lab found that changes in clearance parameters were correlated with changes in the surface expression of Glu transporters (Nickell et al, 2007). Previous studies for DA in the Str, and NAc of F344 rats demonstrated that signal amplitudes of the applied neurotransmitter normalized for the amount applied, was correlated with B_{\max} -values for DA transporters (as assessed by radioligand binding and uptake studies; Hebert and Gerhardt, 1999). Our correlation of relative *in vivo* B_{\max} -values (amplitude per nanoliter of applied Glu, see Table 1) did not demonstrate significant differences between DRD4^{+/+}, DRD4^{+/-}, and DRD4^{-/-} mice. However, additional direct studies of the surface expression of Glu transporters on glia and neurons, and kinetic studies in the different animal groups are needed.

The mechanism by which resting levels of Glu are significantly increased in this study as a result of altered DRD4 expression is unknown, but several possibilities exist. The DRD4 has been localized to the axonal projections of glutamatergic corticostriatal neurons in the Str, where it can regulate the release of Glu (Berger et al, 2001). It was shown by Maura et al (1988) that activation of presynaptic DA D2-like receptors inhibits Glu release in striatal synaptosomes from rats. We have reported in previous work that extracellular DA is significantly decreased in the Str/NAc of DRD4^{-/-} mice (Thomas et al, 2007). Therefore, decreased activation of D2-like family receptors could lead to the resultant increase in resting Glu release. Corticostriatal projections can also provide a mechanism for increased resting Glu levels in the Str. The D4 receptor is also known to be postsynaptic in the prefrontal cortex and can influence resting Glu levels in the Str by inhibiting cell firing of the pyramidal neurons and the tonic function of the terminating synapses in the Str and NAc. When removing the D4 receptor, the inhibition is removed and these neurons fire more spontaneously (Rubinstein et al, 2001). This could account for the increase in tonic firing, which can also contribute to the increased resting levels of Glu seen in the Str. Contributions from DRD4 deletion on MSNs can potentially affect retrograde messengers (Thomas et al, 2007) as well as contribute to possible dysfunction in the striatopallidal pathway, which may facilitate a feed-forward effect of DRD4 loss within the cortico-striatal-thalamic circuit. The relative contributions of metabolic and neuronal pools of Glu to resting levels of Glu and the role of D4 receptors in astrocytic regulation of Glu still requires investigation.

One discrepancy we did not expect in these data was changes in the Str and not in the NAc. We know this is not due to changes in the MEA over time, because previous experiments have shown that Glu-selective sites maintain comparable sensitivity to Glu up to 7 days post implantation within the brain parenchyma (Rutherford et al, 2007). The organization of the corticostriatal projections are such that glutamatergic pyramidal neurons that have cell bodies mostly in lamina 5 (with some in 3 and 6) of the frontal cortex project to the Str and NAc (McGeorge and Faull, 1989). The DRD4 have a cellular distribution to these pyramidal neurons in lamina 5 (and some in 3) (Noain et al, 2006; Mrzljak et al, 1996; Ariano et al, 1997b); although Berger et al (2001) reported DRD4 localization mainly to layers 2–4 with only small amounts in 5. Our Glu and KCl data were taken from the dorsomedial Str, which has projections from the visual, cingulate, agranular insular cortex, motor 2 regions, and auditory parts of the cerebral cortex (McGeorge and Faull, 1989). The NAc has projections from similar areas, such as infralimbic and cingulate areas, but there is an increasing amount

of projections from the hippocampus, entorhinal cortex, piriform cortex, amygdala, and subiculum (McGeorge and Faull, 1989). There is indication that these areas projecting to the NAc may have lower amounts of DRD4 influence (as compared with striatal projections) and, therefore, may not be as affected by loss of the DRD4, which may explain why we see data trends (Noain et al, 2006). Also, Rivera et al (2002) reported higher local expression of DRD4 in the Str in comparison with the NAc of rats, but the presence of DRD4 in these areas is debated (Noain et al, 2006). Our recordings were made in the NAc core. Changes in Glu due to DRD4 alterations are possible in the nucleus accumbens shell, but this area was not measured and needs to be studied.

One caveat of transgenic mice is that compensatory effects may be contributing to the neurochemical effects that we measured. The DRD4^{-/-} mice have been found to have increased expression of DA D1 receptors (DRD1) (+ 42%) and NMDA receptors (+ 40%) within the Str. Likewise, increased DRD1 (+ 39%) and NMDA (+ 31%) receptors in the NAc were also seen in DRD4^{-/-} mice in comparison to DRD4^{+/+} mice. NMDA receptors in the hippocampal CA1 and CA3 regions were also increased (21 and 25%). There were no changes in the amounts of DA D2 receptors (DRD2), AMPA, or kainate receptors between genotypes (Gan et al, 2004). Another study showed that DRD4^{-/-} mice expressed a nine-fold increase of DRD2s in the high-affinity state in comparison with DRD2s in the low-affinity state, whereas the DRD2 protein levels remained similar in both genotypes (Seeman et al, 2005). It has been shown that high-affinity DRD2s tend to be autoreceptors (Cooper et al, 2003). The compensatory effects on Glu neurotransmission resulting from increased levels of D1, NMDA, and D2 high-affinity receptors could be contributing to the findings reported in this paper and need to be investigated. Regardless, the compensatory effects pinpoint the importance of the DRD4 signaling in the Str and strengthen the importance of DA and Glu interactions in these areas.

There is an increasing amount of research supporting a role for the Str in ADHD neurobiology (Durstun et al, 2003; Lou et al, 1989; Teicher et al, 2000). Furthermore, there is a growing interest in the role of Glu, whether it is through DA/Glu interactions or dysregulation of Glu neurotransmission, as a potential contributor to ADHD symptomatology (Carrey et al, 2003, 2007; MacMaster et al, 2003; Russell et al, 2005). Additionally, Carrey et al (2007) found evidence of increased levels of Glu in the Str of ADHD patients by ¹³C magnetic resonance imaging (MRI), which complemented the proton magnetic resonance spectroscopy studies done in 2003 (MacMaster et al, 2003). There is also evidence of striatal dysfunction in ADHD patients shown by emission topography and functional MRI studies (Lou et al, 1989; Teicher et al, 2000).

Various lines of research have correlated the DRD4 with behaviors and drug mechanisms, but the underlying neurochemistry of the DRD4 is not well understood. Using transgenic mice, we have demonstrated that alterations in DRD4 expression can alter multiple neurotransmitter systems, in this case, Glu. These studies support the role of DRD4 in presynaptic Glu regulation and suggest that alterations in DRD4 may lead to alterations in Glu function. Further studies will be needed to address the mechanisms involved.

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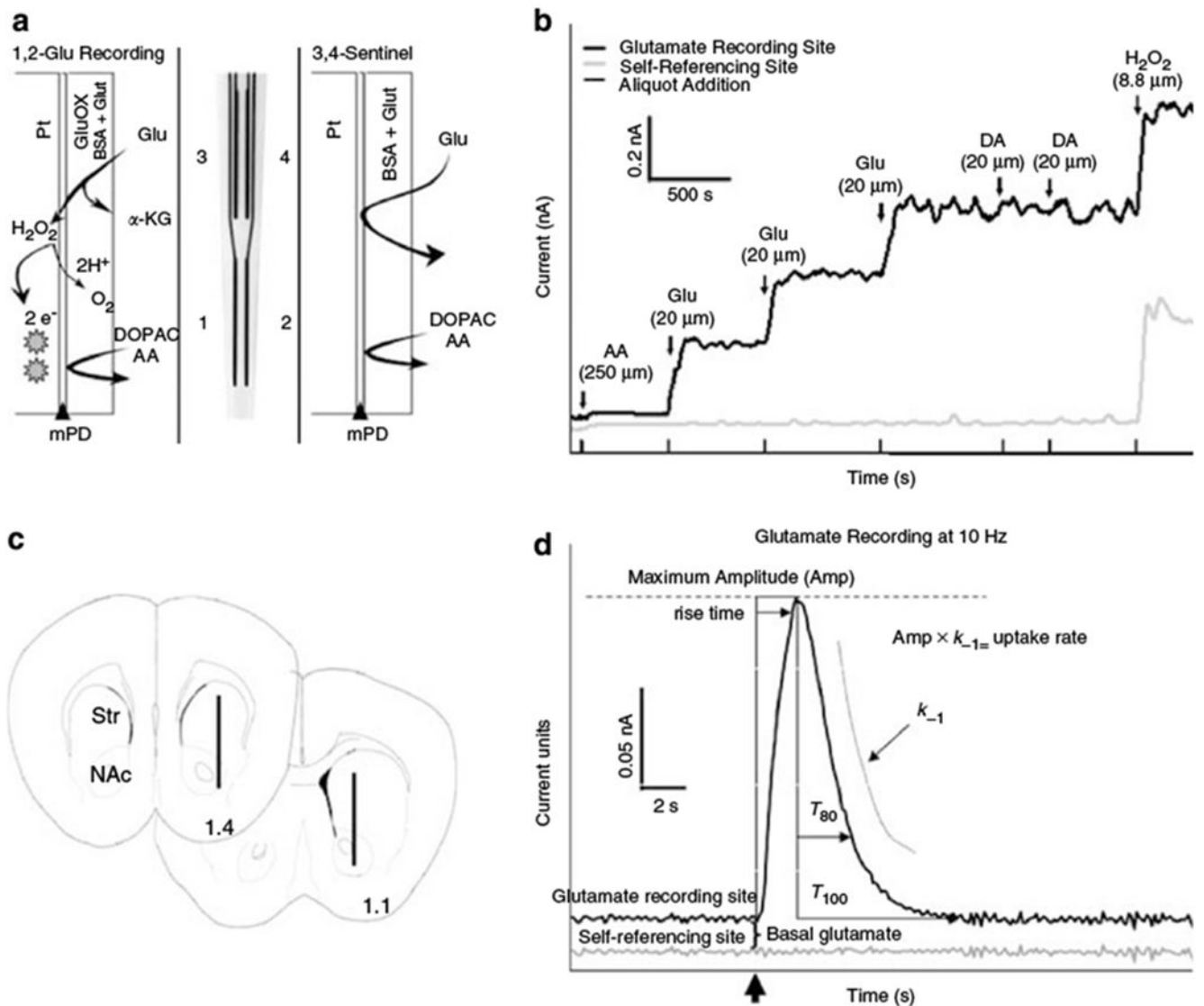
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**Figure 1.**

(a) Schematic diagram of multisite enzyme-based MEA showing the coating layers and configuration of Pt recording sites. These MEAs are designed for self-referencing recordings that provide real-time measures of Glu clearance and resting extracellular Glu levels. Sites 1 and 2 are prepared to measure Glu by coating with a mixture of Glu-ox, BSA, and Glut. Sites 3 and 4 serve as self-referencing sites and are coated with only BSA and Glut. An electroplated layer of mPD forms a size-exclusion layer minimizing electroactive molecules (AA, DA) from interacting with the electrode sites. The size of the electrode sites is $15 \times 333 \mu\text{m}$. The distance between the pairs of electrodes (1/2 vs 3/4) is $100 \mu\text{m}$. The distance between sites 1 and 2 is $30 \mu\text{m}$. (b) A representative recording from *in vitro* MEA calibration. Only one Glu recording site and one self-referencing site are represented. The vertical bars on the *x*-axis represent the addition of each analyte (AA, Glu, DA, and H₂O₂). AA has little effect on the baseline on the MEA sites. Three sequential additions of 20 mM Glu ($40 \mu\text{l}$ each) resulted in stepwise increases in current recorded for site 1. Two aliquots of DA are

added to ensure mPD integrity (as DA is easily oxidized on a Pt surface at an applied potential of 0.7 V). A final aliquot of peroxide (H_2O_2) is used to ensure that all channels are working. (c) MEA placement within the mouse Str and NAc. The diagram shows the approximate location of the Glu recording sites within the Str and NAc at locations 1.1 and 1.4 mm from bregma (modified from Franklin and Paxinos, 1997). The MEA was moved in 350 μm increments throughout the dorsomedial Str and NAc. (d) Representative Glu clearance recording in mouse Str. A recording of Glu clearance in the Str of a DRD4 $+/+$ mouse. The large arrow on the x -axis indicates the time point of local application of exogenous Glu. The time from local application to maximum amplitude of the signal is referred to as rise time. Once the maximum amplitude is reached, three separate measurements are acquired as Glu is cleared from the extracellular space: the uptake rate constant (k_{-1}), the uptake rate, and the T_{80} . The T_{80} is the time point at which 80% of the Glu is cleared in reference to the maximum amplitude (Cass et al, 1993; Cass and Gerhardt, 1995).

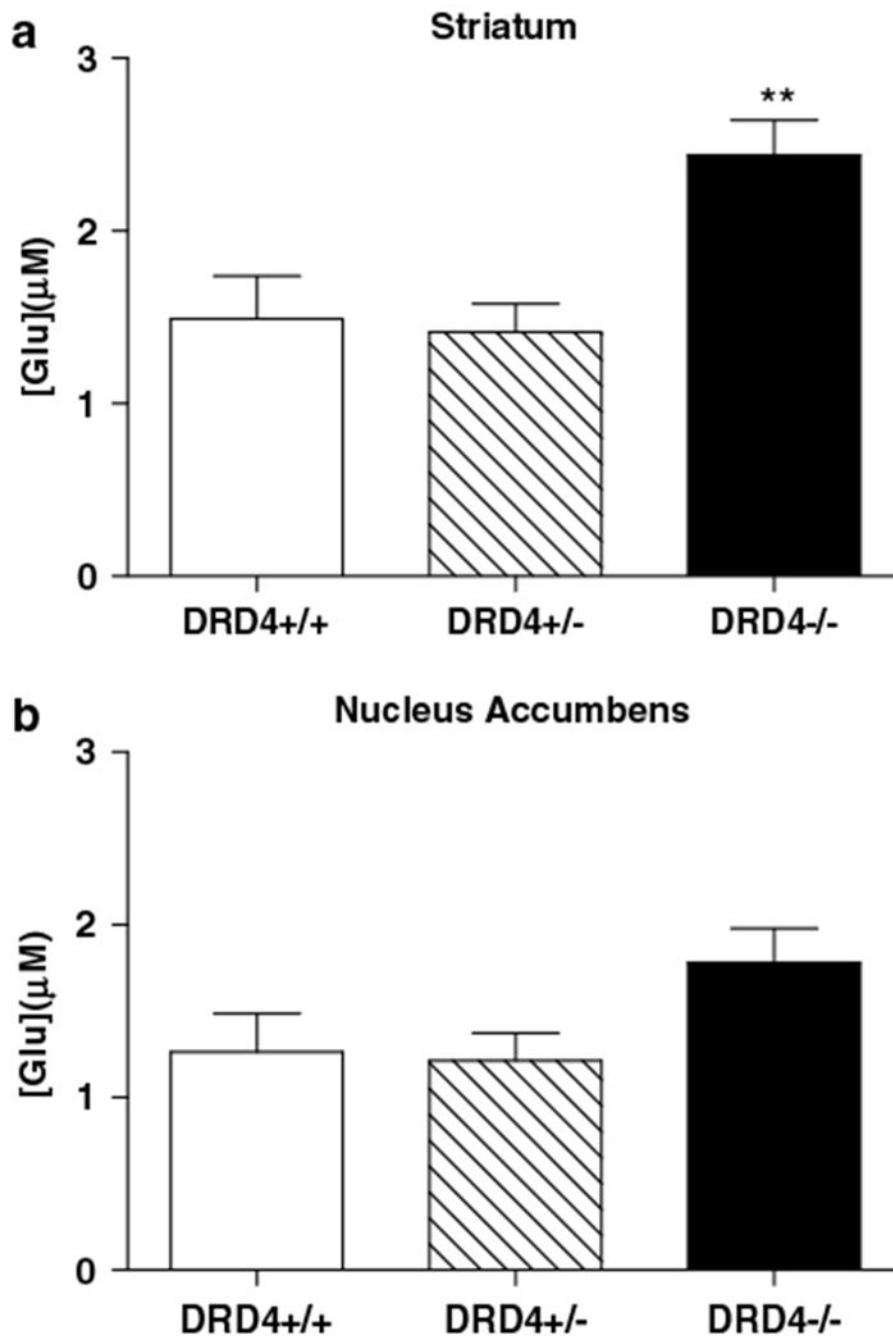


Figure 2. Resting extracellular Glu levels in the Str and NAc. (a) This bar graph demonstrates the differences in extracellular levels of Glu in the Str of DRD4+/+, DRD4+/-, and DRD4-/- (** p <0.01). (b) Extracellular levels of Glu in the NAc did not significantly differ from each other. Values represent the mean \pm SEM.

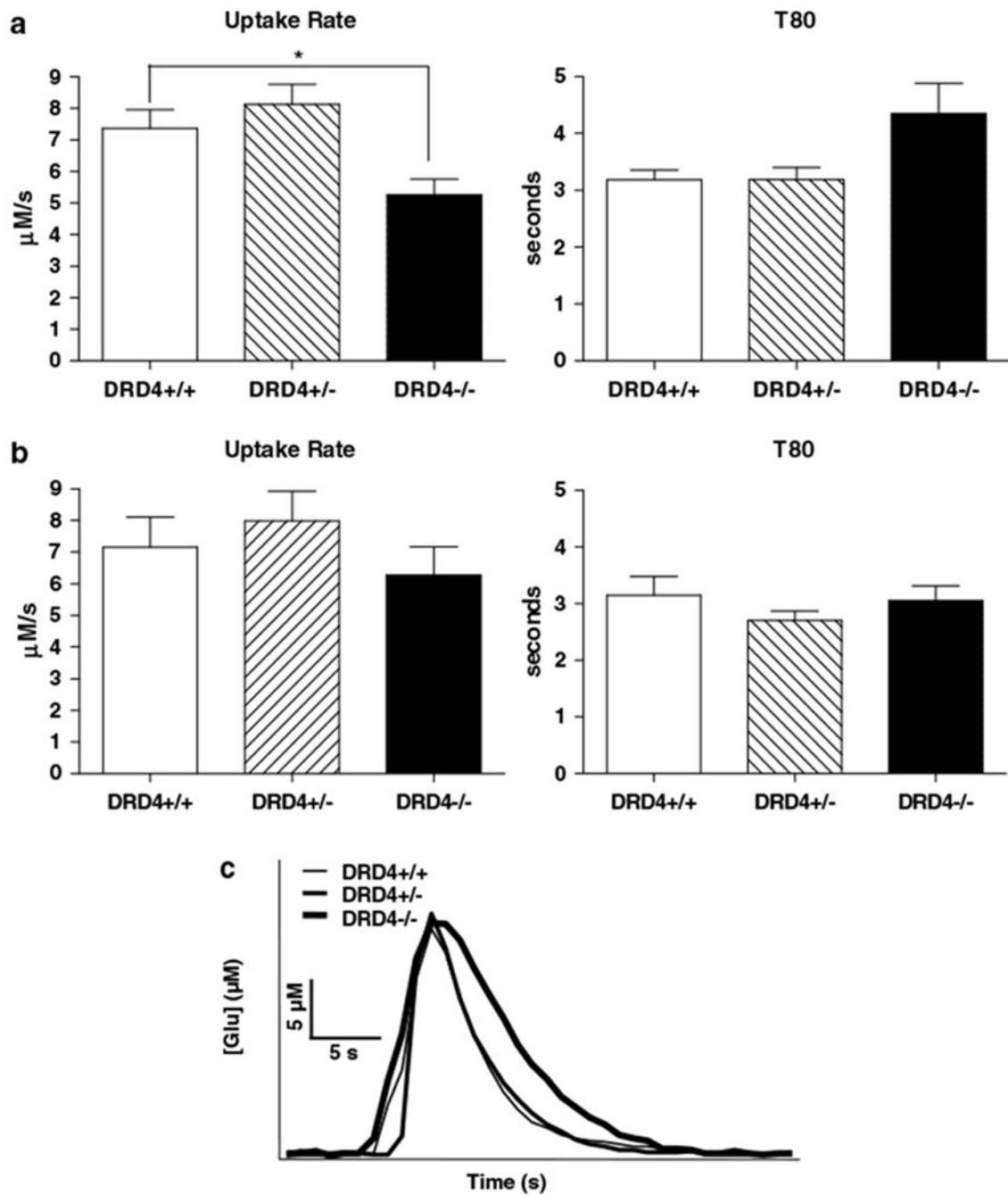


Figure 3.

Glu clearance in the Str and NAc. (a) The bar graphs demonstrate changes in Glu clearance in the Str as a function of DRD4 expression. Uptake rate is significantly slower in the DRD4^{-/-} mice in comparison with their DRD4^{+/+} littermates ($*p < 0.05$), and there was a trend for the T_{80} values to be longer in DRD4^{-/-} mice. (b) The bar graphs show no significant changes in Glu clearance parameters in the NAc. Values represent the mean \pm SEM. (c) Amplitude-matched recordings resulting from local application of Glu demonstrate

differences seen in Glu clearance parameters from DRD4+/+ , DRD4+/-, and DRD4-/- mice in the Str.

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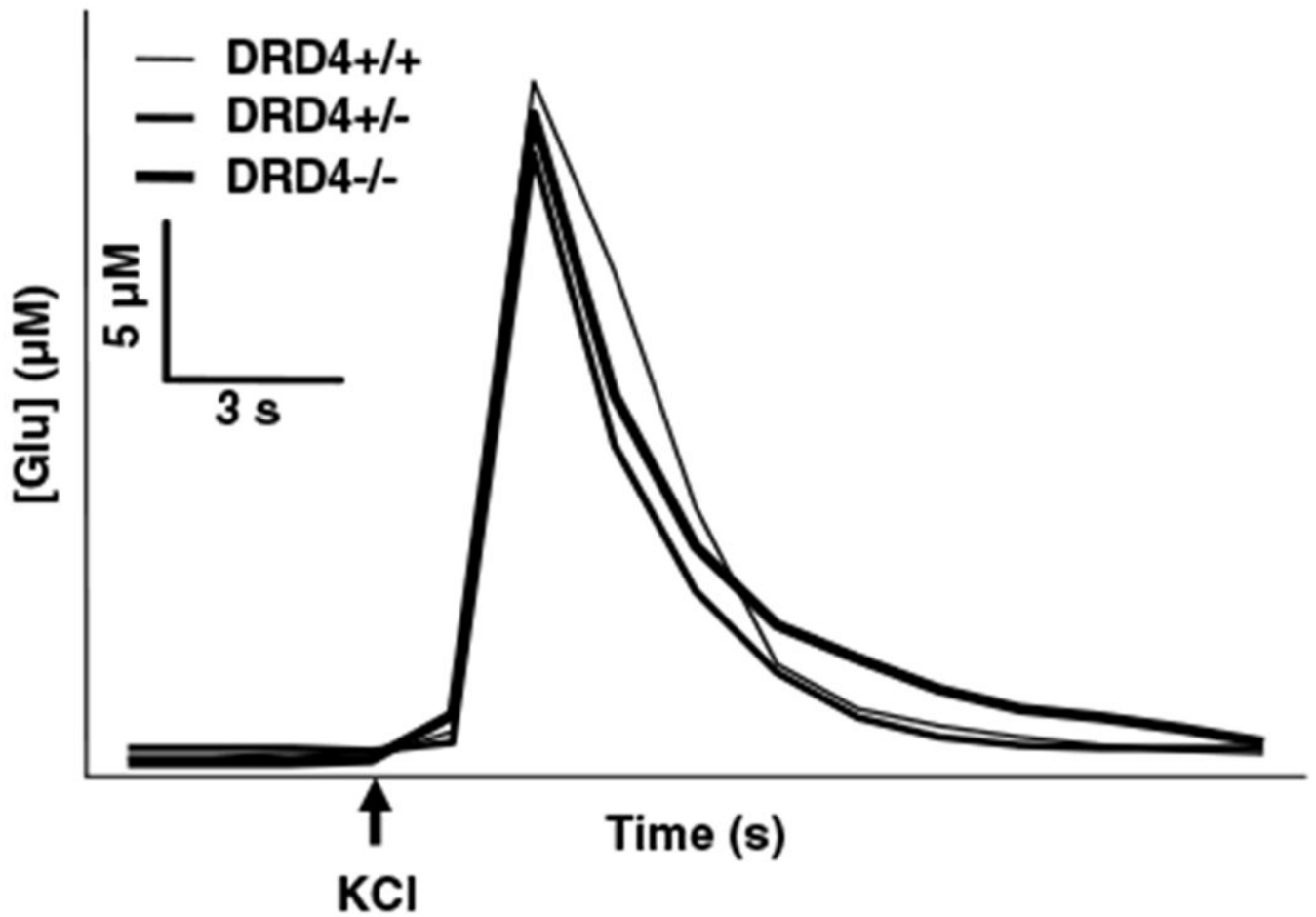


Figure 4. KCl-evoked Glu release in the mouse Str. Recordings of Glu signals evoked by locally applied KCl solution are shown. These signals were similar in amplitude and clearance time in both the Str and NAc.

Table 1

Capacity of Tissue to Clear Exogenous Glu

	Genotype	Volume (nl)	Amplitude (μ M)	Amplitude per nanoliter (μ M/nl)
Striatum	DRD4+/+ (<i>n</i> = 8)	42.7 \pm 3.6	21.5 \pm 1.4	0.72 \pm 0.08
	DRD4+/- (<i>n</i> = 8)	45.4 \pm 4.3	18.5 \pm 1.6	0.55 \pm 0.09
	DRD4-/- (<i>n</i> = 9)	43.1 \pm 4.8	17.4 \pm 1.4	0.59 \pm 0.09
Nucleus accumbens	DRD4+/+ (<i>n</i> = 8)	41.0 \pm 5.7	18.0 \pm 1.2	0.95 \pm 0.23
	DRD4+/- (<i>n</i> = 8)	41.5 \pm 5.9	17.5 \pm 1.8	0.72 \pm 0.18
	DRD4-/- (<i>n</i> = 9)	40.5 \pm 5.7	17.3 \pm 1.6	0.73 \pm 0.19

Similar volumes of exogenous Glu resulted in similar amplitudes and amplitudes per nanoliter measures in the Str and NAc (mean \pm SEM).

Table 2

KCl-Evoked Glu Release Data

	Genotype	Volume (nl)	Amplitude (μM)	Amplitude per nanoliter ($\mu\text{M}/\text{nl}$)
Striatum	DRD4+/+ (n = 6)	39.6 \pm 5.3	22.7 \pm 5.8	0.78 \pm 0.21
	DRD4+/- (n = 6)	41.8 \pm 8.5	12.9 \pm 1.9	0.61 \pm 0.17
	DRD4-/- (n = 9)	41.6 \pm 4.7	14.5 \pm 3.3	0.52 \pm 0.11
Nucleus accumbens	DRD4+/+ (n = 6)	40.7 \pm 6.5	15.8 \pm 5.2	0.88 \pm 0.46
	DRD4+/- (n = 6)	39.6 \pm 5.0	7.5 \pm 1.0	0.23 \pm 0.03
	DRD4-/- (n = 8)	41.0 \pm 4.6	9.9 \pm 2.3	0.34 \pm 0.11

Similar volumes of 35 mM KCl applied to the Str and NAc resulted in robust Glu release but no significant differences due to genotype were observed (mean \pm SEM).