The Reinforcing Properties and Neurochemical Response of Ethanol within the Posterior Ventral Tegmental Area are Enhanced in Adulthood by Peri-Adolescent Ethanol Consumption


Department of Psychiatry, Institute of Psychiatric Research, Indiana University School of Medicine, Indianapolis, IN 46202 (JET, GAD, SRH, EAE, RLB, JMM, WAT, WJM, ZAR)
Running Title: Adolescent EtOH Adult Mesolimbic Dopamine

Address Correspondence to:
Dr. Jamie E. Toalston
Indiana University School of Medicine
Institute of Psychiatric Research
791 Union Drive
Indianapolis, IN 46202-4887 USA

Phone: 317-274-0105; Fax: 317-274-1365; e-mail: jtoalsto@iupui.edu

Number of Text Pages: 23
Number of Figures: 4
Words in Abstract: 250
Words in Introduction: 1061
Words in Discussion: 1183

Non Standard Abbreviations:
Alcohol-preferring rats (P)
Artificial cerebrospinal fluid (aCSF)
Dopamine (DA)
Ethanol (EtOH)
Intracranial Self-Administration (ICSA)
Meso-cortico-limbic (MCL)
Nucleus accumbens (Acb)
Nucleus accumbens shell (AcbSh)
Posterior ventral tegmental area (pVTA)
Post-natal day (PND)
Prefrontal cortex (PFC)
Ventral tegmental area (VTA)
Abstract

Alcohol drinking during adolescence is associated in adulthood with increased alcohol drinking and rate of alcohol dependence. Research examining the biological consequence of adolescent ethanol (EtOH) consumption on the response to EtOH in the neurocircuitry shown to regulate drug reinforcement is limited. The experiments were designed to determine the effects of peri-adolescent alcohol drinking on the reinforcing properties of EtOH within the posterior ventral tegmental area (pVTA) and the ability of EtOH microinjected into the pVTA to stimulate dopamine release in the nucleus accumbens shell (AcbSh). EtOH access (24-hour free-choice) by alcohol-preferring (P) rats occurred during post-natal day (PND) 30-60. Animals were tested for response to EtOH after PND 85. Intracranial self-administration techniques were performed to assess EtOH self-infusion into the pVTA. In the second experiment, rats received microinjections of EtOH into the pVTA and dialysis samples were collected from the AcbSh. The results indicate that in rats that consumed EtOH during adolescence the pVTA was more sensitive to the reinforcing effects of EtOH (lower concentration of EtOH supported self-administration) and the ability of EtOH microinjected into the pVTA to stimulate DA release in the AcbSh was enhanced (sensitivity and magnitude). The data indicate that EtOH consumption during adolescence altered the mesolimbic DA system to be more sensitive and responsive to EtOH. This increase in the response to EtOH within the mesolimbic DA during adulthood could be part of biological sequelae that are the basis for the deleterious effects of adolescent alcohol consumption on the rate of alcoholism during adulthood.
Introduction

For the vast majority of people in the United States, the initiation of alcohol use begins during adolescence. A high percentage (12%) of adolescents begin using alcohol during middle school (8th grade), and prior to high school graduation the vast majority of people in the United States (80-90%) have consumed alcohol (Johnston et al., 2004). In combination with moderate alcohol consumption, adolescents engage in binge drinking episodes. Self-reports have indicated that 22 and 28% of 10th and 12th grade students, respectively, reported an incident of binge drinking within the past two weeks (Johnston et al., 2004). College students report a previous high level of binge drinking during high school (70%), frequent on-going episodes of binge drinking during college (44%), and a subset of college students are frequent binge drinkers (19-25% report more than 3 episodes of binge drinking per week; Wechsler et al., 1995, 2000; SAMHSA, 2006).

Alcohol consumption during adolescence is associated with a number of deleterious consequences. Age of first drink and the propensity to have binge EtOH drinking episodes during adolescence is associated with increased alcohol involvement, heavier drinking bouts, arrests for driving with ability impaired, and an increased rate of alcohol dependence during adulthood (Hingson et al., 2006, 2008; Chou and Pickering, 1992). Epidemiological studies have indicated a 1.3 to 1.6 times increased rate of alcohol dependence in individuals who initiate alcohol use prior to the age of 15 (Dawson et al., 2008). The deleterious effects of adolescent EtOH consumption on adult alcohol dependence are compounded in individuals with a family history of alcoholism (Agrawal et al., 2009; Jacobus et al., 2009).

The neurological remodeling of the adolescent brain is extensive and includes cortical and limbic regions (Spear, 2000). In general, early adolescence is marked by an overproduction
of axons and synapses followed by a rapid pruning during late adolescence (Giedd, 2004). For example, glutamatergic projections into the prefrontal cortex (PFC) increase during early adolescence and subsequently significantly reduce by dendritic pruning and synaptic regression during late adolescence (Zecevic et al., 1989). Similar patterns of growth and pruning are observed in the hippocampus, nucleus accumbens (Acb), amygdala, hypothalamus, ventral tegmental area (VTA), and further cortical regions (c.f. Giedd, 2004; Gulley and Juraska, 2013). It is the interaction between adolescent EtOH drinking and the neurological flux of adolescence that is thought to produce the enduring deleterious consequences observed in adult alcoholics.

Neurotransmitter systems are also altered through the transitional process of adolescence. Excitatory inputs into the Acb and VTA are pruned with an associated reduction in glutamate receptors in those areas during adolescence (Thomas et al., 2001). The glutamate system is involved in plasticity and learning and is directly modulated by EtOH. Thus, the glutamatergic system has been hypothesized to be a potential system that regulates the enduring effects of adolescent binge EtOH drinking (Crews et al., 2007; Carpenter-Hyland and Chandler, 2007). Similarly, serotonergic innervation of the meso-cortico-limbic (MCL) system peaks during adolescence and is subsequently reduced through dendritic pruning (Rosenberg and Lewis, 1994). In particular, the 5HT$_{2A}$ receptor expression peaks during adolescence in the PFC and limbic regions (VTA), but are reduced during maturation (Morilak and Ciaranello, 1993). A consequence of adolescent EtOH binge drinking is an increase in adult levels of serotonin transporters, possibly indicating alterations in serotonin activity (Monti et al., 2005). The reorganization of the dopamine system during adolescence is regional and receptor subtype specific (Tarazi and Baldessarini, 2000). In the MCL system (PFC, VTA and Acb), the numbers of dopamine neurons peak during adolescence, and subsequent pruning in these areas is
associated with maturation of reward and motor pathways (c.f., Crews et al., 2007). The glutamatergic and serotonergic systems directly activate VTA DA neurons in adults. Alterations in these neurotransmitter systems within the VTA by adolescent EtOH consumption may alter the response of the VTA to EtOH during adulthood (c.f., McBride et al., 2005).

Adolescent EtOH consumption can alter the mesolimbic dopamine system. Adolescent EtOH consumption (Sahr et al., 2004), as well as peripheral EtOH injections (Bandanich et al., 2007) can increase basal dopamine levels or dopamine reuptake in the AcbSh during adulthood. Similar results are not produced in adult rats with comparable EtOH exposure paradigms (Pascual et al., 2009). The mesolimbic dopamine system is altered in response to non-EtOH stimuli during adulthood following adolescent EtOH consumption. Consumption of EtOH during adolescence in rats results in greater DA release in the AcbSh following ‘risky’ choice responding compared to adolescent naïve controls (Nasrallah et al., 2011).

Peri-adolescent alcohol drinking by alcohol preferring (P) rats has been reported to produce long-lasting alterations in the reinforcing effects of EtOH, as indicated by P rats with access to EtOH, compared to the water control group, acquiring acquisition of EtOH operant responding sooner, showing a greater resistance to extinguish responding, and having a more prolonged elevated level of relapse responding for EtOH (Rodd-Henricks et al., 2002a). However, CNS mechanisms underlying these long-lasting alterations have not yet been explored.

In naïve rats, EtOH is directly self-administered into the posterior, but not anterior, VTA (Rodd-Henricks et al., 2000). The reinforcing properties of EtOH within the pVTA are dependent upon activation of VTA DA neurons (Rodd et al., 2005a). Selective breeding for high alcohol preference (P rats) is associated with an increase in the sensitivity of the pVTA to the reinforcing properties of EtOH compared to Wistar rats (lower concentrations required to support
self-administration; Rodd et al., 2004; 2005a). Chronic EtOH consumption (>10 weeks 24-hour free choice access) can further reduce the concentration of EtOH required to support self-administration directly into the pVTA (Rodd et al., 2005b). Exposure to repeated periods of excessive EtOH consumption can enhance the magnitude of EtOH self-administration (higher rate of self-administration for equivalent concentration) in P rats (Rodd et al., 2005c). The biological bases for these effects are unknown.

The current experiments were designed to determine the effects of adolescent EtOH consumption on the actions of EtOH within the mesolimbic DA system during adulthood. The first experiment determined if adolescent EtOH consumption would alter the self-infusion of EtOH directly into the pVTA. The second experiment determined if adolescent EtOH consumption would alter the effects of EtOH microinjected directly into the pVTA to stimulate DA release in the AcbSh. The overall hypothesis was that adolescent EtOH consumption should enhance the reinforcing properties of EtOH within the pVTA and promote EtOH’s ability to stimulate the mesolimbic DA system.

Methods

Subjects

The adolescent EtOH access procedures used herein followed published procedures from our laboratory (Rodd-Henricks et al., 2002a, Bell et al., 2003, 2004, 2006, Sahr et al., 2004). Male P rats were chosen for use in the current study because their rapid growth post-adolescence increases skull strength for earlier cannula placement surgery. Previous work (McKinzie et al., 1998a, Bell et al., 2003) has described the differences between male and female P rats in EtOH drinking at these ages as minimal. The main benefit of using the P rats is that they voluntarily
consume pharmacologically relevant levels of EtOH during adolescence, thus avoid stress of other administration procedures (e.g., repeated injections).

Animals were maintained in facilities fully accredited by the Association for the Assessment and Accreditation of Laboratory Animal Care. All research protocols were approved by the Indiana University School of Medicine (Indianapolis, Indiana) Institutional Animal Care and Use Committee and were in accordance with the guidelines of the Institutional Care and Use Committee of the National Institute on Drug Abuse, the NIH, and the Guide for the Care and Use of Laboratory Animals (2011).

Peri-Adolescent EtOH Exposure Procedure

Pups were single-housed in hanging stainless steel cages (Allentown Caging Equipment Co, Allentown, New Jersey) on PND 28. Subjects were initially maintained on a 12-hour light/dark cycle, lights on at 0900. On PND 30, subjects received either ad lib water or continuous access to 15% v/v EtOH and water, until PND 60 as previously described (Rodd-Henricks et al., 2002a). Food was available ad lib. Bottle and body weights for all subjects were recorded every other day.

On PND 60, EtOH access ceased, and subjects were pair-housed in standard shoebox cages, within the same treatment condition. Subjects were also immediately transferred to a 12-hour reverse dark/light cycle, lights off at 1000, to optimize rats' nocturnal activity levels for later procedures. After PND 60, subjects received no further oral EtOH intake experience.

Intracranial self-administration (ICSA) procedure

Test chambers (Coulbourn Instruments, Allentown, Pennsylvania) were situated in sound-attenuating cubicles, as described previously (Rodd-Henricks et al., 2000, Rodd et al.,
ICSA was performed as previously described (Rodd-Henricks et al., 2000, Rodd et al., 2004). After postnatal day 75, the rats were implanted under isoflurane anesthesia with a guide cannula (22 gauge, Plastics One) stereotaxically aimed 1.0 mm above the pVTA. Coordinates were 5.8 to 6.1 mm posterior to bregma, 2.1 mm lateral, and 8.5 mm ventral from the surface of the skull at a 10 degree angle from the vertical (Paxinos and Watson, 1986). A place-holding stylet (28 gauge, Plastics One) extending 0.5 mm beyond the tip of the guide cannula was inserted at all times, except during test sessions. Subjects were single-housed post surgery, and allowed to recover for 7 days. Starting three days prior to testing, subjects were handled 5 min per day.

All infusates were prepared freshly on the day of the experiment. Artificial cerebrospinal fluid (aCSF) was used as the vehicle for ICSA infusions. This injection vehicle consisted of (in mM) 120.0 NaCl, 4.8 KCl, 1.2 KH2PO4, 1.2 MgSO4, 25.0 NaHCO3, 2.5 CaCl2, and 10.0 D-glucose, all filtered through a sterile filter (pore size 0.2 µM) as previously described (Rodd-Henricks et al., 2000, Rodd et al., 2004b). Ethyl EtOH (190 proof; McCormick Distilling Co., Weston, Missouri) was dissolved in the vehicle solution to the correct concentration. When necessary, 0.5 N HCl was added to adjust the pH to 7.4 (±0.1).

ICSA was conducted similar to procedures previously described (Rodd-Henricks et al., 2000, Rodd et al., 2004). Briefly, subjects were brought to the testing room, the stylet was removed, and an injection cannula/infusate cylinder was affixed in place. The injection cannula extended 1.0 mm beyond the tip of the guide, into the pVTA. A single, noncontingent administration of infusate was given at the beginning of the session during this insertion procedure in order to prime the system. Test sessions occurred every other day. No operant shaping techniques were used. Active lever and inactive lever sides were counterbalanced.
between subjects, remaining the same for each individual rat. Within each 4 hr session, responses on the active lever resulted in 5 sec infusions on a fixed ratio 1 schedule of reinforcement. During infusion and time-out (5 sec), responses on the active lever were recorded, but did not produce further infusions. Responses on the inactive lever were recorded but did not result in infusions at any time; these responses were used to index non-specific bar-pressing activity.

During ICSA sessions 1 through 4 (acquisition), subjects received their respective dose of either the aCSF vehicle or EtOH. During ICSA sessions 5 and 6 (extinction), all subjects received aCSF vehicle only, and in session 7 (reinstatement), the original concentration was made available.

A total of 82 P males were used in the experiment (n = 41/41 adolescent naïve/adolescent drinkers). Rats from the adolescent groups were randomly assigned to groups that self-administered 0 (aCSF), 50, 75, 100, or 150 mg% EtOH directly into the pVTA (adolescent naïve - n = 6-10/group; adolescent drinkers - n = 7-10/group).

**Microinjection-Microdialysis Procedure**

Experimental housing was composed of Plexiglas chambers (40 x 28 x 40 cm). Polyethylene tubing connected to a dedicated Harvard pump (Harvard Apparatus, Holliston, Massachusetts) was used to administer aCSF continuously throughout the experiment for microdialysis in the AcbSh. The connection to the EMIT unit for microinjection administration to the pVTA was identical to that used in the ICSA experiment, although automated control of injections was programmed into the unit (Isolated Pulse Stimulator Model 2100, A-M Systems Inc, Sequim, Washington), instead of the separate computer controlling and recording operant self-administration.
Microdialysis probes were prepared as approximately 2-mm loop style probes, as previously described (Perry and Fuller, 1992, Engleman et al., 2000, Melendez et al., 2002). Probes were manufactured in the laboratory with regenerated cellulose Spectra/Por® hollow fiber microdialysis tubing, molecular weight cut off of 13,000. In our laboratory, these have been previously found to have approximately 15% DA recovery, which is an average recovery rate for this design and probe length (Justice, 1993).

Adolescent EtOH treatment occurred as in the first experiment. Food and water were available ad lib at all times, except during Microinjection-Microdialysis testing. Microinjection-Microdialysis was performed as previously described (Ding et al., 2011). After PND 75, and under isoflurane anesthesia, a microinjection guide cannula (22 gauge, Plastics One) was implanted in the right hemisphere of each subject, stereotaxically aimed 1.0 mm above the pVTA. Coordinates were 5.8 to 6.1 mm posterior to bregma, 2.1 mm lateral, and 8.5 mm ventral from the surface of the skull at a 10 degree angle from the vertical (Paxinos and Watson, 1986). A place-holding stylet (28-gauge, Plastics One) extending 0.5 mm beyond the tip of the guide cannula was inserted at all times, except during final experimentation. Also in the right hemisphere, a guide cannula (18 gauge, Plastics One) was implanted, aimed 3.0 mm above the AcbSh. Coordinates were 1.7 mm anterior to bregma, 2.3 mm lateral, and 5.4 mm ventral to the surface of the skull at a 10 degree angle from the vertical (Paxinos and Watson, 1986). A place-holding stylet (Plastics One) extending 0.5 mm was inserted at all times, except during final experimentation.

Subjects were single-housed post surgery, and allowed to recover 6 days. Three days prior to testing, subjects were habituated to the testing chambers, 3 hours per day. One day before testing, microdialysis probes were inserted into the AcbSh under isoflurane anesthesia.
When inserted, the dialyzing loop was oriented in an anterior-posterior direction to maximize exposure to the AcbSh. The probe extended 3 mm below the guide cannula, into the AcbSh.

The next day, the Microinjection-Microdialysis procedure was performed. Subjects were placed in the experimental chambers and the microdialysis probe tubing was connected to the pump for aCSF perfusion. The aCSF microdialysis perfusion medium was composed (in mM) as has been previously described (Melendez et al., 2002) of 145.0 NaCl, 2.7 KCl, 1.0 MgCl2, 2.5 CaCl2, and 2.0 Na2HPO4, filtered through a sterile filter (pore size 0.2 µM), always prepared fresh the day of the procedure. When necessary, pH was adjusted to 7.4 with 0.1 N acetic acid.

Flow speed of the perfusion medium was 1 µL/min. Microdialysis outflow was collected for 15 min per sample. After at least 90 min of washout flow, at least three baseline dialysate samples were collected. This was followed by one microinjection dialysate sample.

During the microinjection sample, the pVTA-cannula stylet was removed and the injection cannula/infusate cylinder affixed in place. The injection cannula extended 1.0 mm beyond the tip of the guide, into the pVTA. Administration of infusate occurred automatically, as programmed into the EMIT machine. Each subject received microinjections of one solution only, prepared identically to that in the ICSA experiment; either infusate vehicle aCSF, or 50, 75, 100, or 200 mg% EtOH. All subjects received the same volume of microinjections. Microinjections were composed of a series of 100 nL boluses, each delivered over an interval of 5 sec. This was repeated every 20 sec for a total of 30 microinjections over a 10 min period into the pVTA.

Following the microinjection sample, 120 min of post-injection dialysate samples were collected. All samples were collected into tubes containing 5 µL of 0.1 N perchloric acid. After collection, samples were immediately frozen on dry ice and stored at -70 degrees C until HPLC analysis for DA content.
A total of 74 P males were used in the microdialysis experiment (n = 37/37 adolescent naïve/adolescent drinkers). Rats from the adolescent groups were randomly assigned to groups that microinjected with 0 (aCSF), 50, 75, 100, or 150 mg% EtOH directly into the pVTA (adolescent naïve - n = 6-10/group; adolescent EtOH drinkers - n = 6-9/group).

All microdialysis samples were analyzed with microbore HPLC-EC to determine extracellular levels of DA. Samples were loaded into a 10 µL sample loop and injected onto an analytical column. Detector output ran to a computer program for analysis (ChromPerfect, Justice Innovations, Inc., Palo Alto, California). DA levels were then determined by comparison with a standard curve. The lower sensitivity limit for DA was estimated to be 0.1 nM. Complete details of HPLC procedure have been previously published (Sahr et al., 2004).

**Histologies**

Upon termination of the experiments, a solution of 1% bromophenol blue dye was injected into the infusion site and the animals sacrificed. Brains were removed and immediately frozen at -70 °C, for slicing into 40-um sections with a cryostat microtome. Slides were stained with cresyl violet and examined for infusion site verification using the atlas of Paxinos and Watson (1986).

**Statistical Analysis**

EtOH consumption was analyzed as pure EtOH intake (grams of EtOH per kilogram of body weight, g/kg). Change in preference ratio for EtOH intake vs. water was calculated by plotting ratios each day of EtOH exposure as a percentage of 15% EtOH solution consumed in relation to total fluids consumed ([(g ethanol solution intake/g ethanol solution intake + g water intake] x 100). The first day of access was compared to the last day of access. Intake and
Preference data were averaged in six blocks of 5 days, analyzed with a repeated measures ANOVA and linear regression between blocks.

ICSA data were analyzed with a Dose x Session mixed ANOVA, with repeated measures on Session performed on the number of active lever responses and the number of infusions separately. For each individual group, lever discrimination was determined by “lever (active vs. inactive) x session” mixed ANOVA with repeated measures on session. Post hoc Tukey’s b tests were employed when a significant main effect was found, p < 0.05. Extinction was determined by comparing the responses on the active lever during sessions 4, 5, and 6, while reinstatement was determined by comparing the responses on the active lever during sessions 5, 6, and 7.

Microdialysis data were expressed as a percentage of basal DA values, to correct for between-subject baseline variability, as previously described (Engleman et al., 2006). Basal dialysate values for each subject were calculated as the mean of three baseline samples prior to the injection sample. Also, absolute levels of baseline DA were calculated, and compared as group means between the two peri-adolescent Exposure Groups. The effects of peri-adolescent EtOH administration on basal extracellular DA levels and maximal drug effect with each Dose was calculated using Student’s t-test. The effects of EtOH microinjection administration on extracellular DA levels as a function of time and adolescent treatment condition were analyzed using a two-way Adolescent Group x Time analysis of variance (ANOVA), with repeated measures on Time (15-min samples), followed by the Tukey’s post hoc test. Alpha was set at a P < 0.05 significance level.

Results

Adolescent EtOH Consumption
Initial consumption for all peri-adolescent EtOH-exposed subjects was 5.17 ±0.36 g/kg/day (data not shown). At the end of the access period, consumption was 7.80 ±0.31 g/kg/day. A repeated measures within subjects ANOVA performed on the average intake in 5 day blocks revealed there was a significant main effect of Day (F5,51 = 5.627, p < 0.001), indicating that EtOH consumption changed over time. There was no significant effect of Study Group (ICSA and Microinjection-Microdialysis groups consumed equivalent amounts of EtOH; F1, 55 = 1.948, p = 0.168). The amount of EtOH consumed would be predicted to produce significant, pharmacologically relevant (> 50 mg%) blood alcohol concentrations (Bell et al., 2003, 2004, 2006).

ICS A EtOH Dose Response

A multifactorial ANOVA was performed on the average number of infusions self-administered from sessions 1-4 (Fig. 1). The analysis indicated a significant Adolescent Group x EtOH concentration interaction (F4,72 = 2.85; p = 0.031). Reducing the interaction term was performed by examining the average number of infusions for each EtOH concentration. In rats self-administering aCSF, 50 mg%, or 150 mg%, there was no effect of Adolescent Group on infusions self-administered (F values < 2.4; p values > 0.14). In contrast, there was a significant difference between Adolescent Group (EtOH > Naïve) in P rats self-infusing 75 or 100 mg% EtOH (F values > 13.76; p values < 0.003). In adolescent naïve rats, there was a significant effect of EtOH concentration on the number of self-infusions (F4,36 = 3.4; p = 0.019). Post-hoc comparisons indicated that adolescent naïve rats received more self-infusions of 150 mg% EtOH than aCSF or 50 mg% EtOH. In the adolescent EtOH drinking rats, there was also a significant effect of EtOH concentration on the number of self-infusions (F4,36 = 14.44; p < 0.0001). Post-hoc comparisons indicated that adolescent EtOH drinkers given 75, 100 or 150 mg% EtOH
received more self-infusions than rats given aCSF or 50 mg% EtOH. In addition, adolescent EtOH drinkers given 50 mg% EtOH received more self-infusions than rats given aCSF.

Examining the number of active and inactive lever responses across all 7 sessions (Figs 2 and 3) revealed a significant Adolescent Group x EtOH concentration x Lever X Session interaction term (F$_{24,280} = 4.26$; p < 0.001). In adolescent naïve rats, there was a significant EtOH concentration x Lever x Session interaction term (F$_{24,136} = 2.82$; p = 0.024). Performing individual ANOVAs on both the active and inactive lever responses for each session indicated only two significantly different sessions of responding. During the 4th operant session, there was a significant effect of EtOH concentration on active lever responding (F$_{4,36} = 3.26$; p = 0.022) with post-hoc comparisons indicating that the 150 mg% EtOH group was significantly different than all other groups (Fig, 3; bottom left panel). In the 7th session, there was also a significant effect of EtOH concentration on active lever responding (F$_{4,36} = 3.52$; p = 0.017) with post-hoc comparisons indicating that the 100 and 150 mg% groups were significantly different than all other groups (Fig, 3; left panels). Analysis for lever discrimination indicated that the adolescent naïve P rats self-infusing 150 mg% EtOH discriminated between responding on the active and inactive lever during sessions 2, 3, 4, and 7 (p values < 0.004). Adolescent naïve P rats given 100 mg% EtOH only expressed lever discrimination during the 7th session (p < 0.001). The 150 mg% EtOH group displayed extinction when aCSF was substituted (sessions 5 and 6), with a significant reduction from session 4 to sessions 5 (p = 0.003) and 6 (p = 0.02). The 100 and 150 mg% EtOH groups displayed reinstatement of EtOH self-infusions (significantly higher level of active lever responding during session 7 compared to session 6; p values < 0.001).

In adolescent EtOH drinkers, EtOH self-infusions occurred at lower concentrations and at a higher levels (Figs. 2 and 3). In adolescent EtOH drinkers, there was a significant EtOH
concentration x Lever x Session interaction term (F_{24,136} = 2.16; p = 0.03). During sessions 1, 2, 3, 4, and 7, there was a significant effect of EtOH concentration on the number of active lever responses (F_{4,36} values > 6.18; p values < 0.001), but there were no significant effects on the inactive lever responding (F_{4,36} values < 1.7; p values > 0.19). Post-hoc comparisons indicated that during sessions 1-4, adolescent EtOH drinkers given 75, 100 and 150 mg% EtOH responded more on the active lever than the aCSF and 50 mg% EtOH groups. During the 7th session, post-hoc comparisons indicated that adolescent EtOH drinkers given 100 and 150 mg% EtOH responded more than the 75 mg% EtOH group, which was significantly higher than the aCSF and 50 mg% groups (100, 150 mg% > 75 mg% > aCSF, 50 mg%). During sessions 2-4, adolescent EtOH drinkers given 75, 100 and 150 mg% EtOH discriminated between the active and inactive levers (p values < 0.014). These groups also reduced active lever responding during aCSF substitution (extinction, p values < 0.025), and reinstated EtOH self-infusion during session 7 (p values < 0.001).

Contrasting the adolescent naïve and EtOH drinkers at each individual EtOH concentration for active lever responding during each session provide evidence for enhanced responding by the adolescent EtOH drinkers. For rats self-infusing 75, 100 and 150 mg% EtOH directly into the pVTA, adolescent EtOH drinkers responded more on the active lever during sessions 2, 3, 4, and 7 than did adolescent naïve rats (all p values < 0.013).

Microinjection-Microdialysis EtOH Dose Response

Similar to the ICSA data, the microdialysis experiment indicated that the pVTA of adolescent EtOH drinkers was more responsive than adolescent naïve rats to EtOH (Fig. 4). Overall, there was a significant Adolescent Group x EtOH concentration x Time interaction term (F_{32,240} = 2.88; p = 0.009). The significant interaction term was initially decomposed by holding
EtOH concentration constant. DA levels in the AcbSh did not differ in adolescent naïve and EtOH drinkers following microinjections of aCSF and 50 mg% EtOH into the pVTA (p values > 0.186). In rats receiving microinjections of 75 mg% EtOH, DA levels in the AcbSh were significantly higher in the adolescent EtOH drinkers compared to adolescent naïve rats (F1,13 values > 7.8; p values < 0.015) during the 1st and 2nd samples following microinjection. Similar analysis revealed that DA levels in the AcbSh were elevated in adolescent EtOH drinkers compared to adolescent naïve rats during the 1st - 6th sample period following microinjection of 100 mg% EtOH (F1,14 values > 6.7; p values < 0.021). The increase in DA levels in the AcbSh following microinjection of 150 mg% EtOH were comparable between adolescent naïve and adolescent EtOH drinkers, except during the 3 sample period immediately following the microinjections (EtOH > naïve; F1,12 = 4.7; p = 0.05).

In adolescent naïve rats (Fig. 4; top panel), there was a significant EtOH concentration x Time interaction term (F24,192 = 3.16; p < 0.001). Performing individual ANOVAs for each sample period revealed significant EtOH concentration differences in the AcbSh during sample periods 1, 2, 3, 5, and 6 following microinjection (F4,32 values > 3.8; p values < 0.013). Post-hoc comparisons indicated that for all these times points, adolescent naïve rats administered 150 mg% EtOH directly into the pVTA had significantly higher DA levels in the AcbSh than all other groups.

In adolescent EtOH drinkers (Fig. 4; bottom panel), there was also a significant EtOH concentration x Time interaction term (F24,192 = 6.25; p < 0.001). Performing individual ANOVAs for each sample period revealed significant EtOH concentration differences in the AcbSh during sample periods 1-7 (Inj - Inj90) following microinjection (F4,32 values > 5.3; p values < 0.002). Post-hoc comparisons indicated during the 1st and 2nd sample period following
EtOH microinjection into the pVTA, the DA levels in the AcbSh of adolescent drinkers receiving 75, 100, and 150 mg% EtOH were higher than rats receiving microinjections of aCSF or 50 mg% EtOH. During the 3rd - 7th sample period following EtOH microinjection into the pVTA, the DA levels in the AcbSh of adolescent EtOH drinkers receiving 100, and 150 mg% EtOH were higher than in subjects receiving microinjections of aCSF, or 50 or 75 mg% EtOH.

**Body Weights**

Adolescent EtOH consumption in P rats did not alter body weight growth (data not shown). Statistical analysis revealed a significant main effect of day (\(F_{7,96} = 1370.7, p < 0.001\)), but no significant main effect of exposure group (\(F_{1,102} = 0.257, p=0.613\)) or Day x Exposure Group interaction (\(F_{7,96} = 1.53, p=0.167\)).

**Discussion**

The findings of the current experiments indicate that peri-adolescent EtOH consumption by male P rat pups produces neuroadaptations that results in individuals being more susceptible to the reinforcing and stimulatory actions of EtOH within the pVTA during adulthood. Specifically, adolescent EtOH consumption results in a greater sensitivity to EtOH (lower concentrations required to establish intracranial self-administration), and a propensity to receive more self-infusions of EtOH at a given concentration within the pVTA (Figs. 1-3). The reinforcing properties of drugs of abuse within the pVTA are thought to be dependent upon stimulation of VTA DA neurons and DA release in the AcbSh (c.f., Deehan et al., 2013). The current data sets indicate a convergence of the effects of adolescent EtOH consumption on the self-infusion of EtOH directly into the pVTA and the ability of EtOH microinjected into the pVTA to stimulate DA release in the AcbSh. Paralleling the self-infusion data, adolescent EtOH consumption resulted in a lower concentration of EtOH required to be microinjected into the...
pVTA to increase DA release in the AcbSh (Fig. 4). In addition, in adolescent EtOH drinkers and naïve subjects given the same concentration of EtOH microinjected into the pVTA, the amount of DA released and the duration of the increase in DA release in the AcbSh was increased by adolescent EtOH consumption (Fig. 4).

The effects of EtOH consumption during adolescence on adult EtOH consumption is inconsistently reported in the literature. However, like every aspect of alcohol studies, the manner, amount, and duration of EtOH exposure is likely to affect the observed consequences of EtOH consumption. Non-physiologically relevant levels of alcohol consumption (EtOH intake levels that would produce no significant blood EtOH concentration) during adolescence have been shown to have no effect on adult EtOH consumption (Slawecki and Betancourt, 2002; Slawecki, 2004; Slawecki et al., 2004; Siegmund et al., 2005). Significant consumption of sweetened EtOH in Sprague-Dawley adolescent rats increases adult consumption of sweetened EtOH but not unadulterated high EtOH concentration solutions (20%; Broadwater et al., 2013). Injections of EtOH during adolescence can result in a conditioned taste aversion to sweetened solutions and indeterminate effects on adult EtOH consumption (Gilpin et al., 2012). In contrast, adolescents injected with EtOH in a manner that does not produce taste aversion can enhance adult EtOH consumption (Pascual et al., 2007, 2009; Maladonado-Devincci et al., 2010). Voluntary EtOH drinking during adolescence at a level that produces pharmacologically relevant levels of EtOH has been shown to enhance adult EtOH consumption (Walker and Ehlers, 2009; Strong et al., 2010; O’Tousa et al., 2013). In P rats, adolescent EtOH consumption (oral free-choice) increases the acquisition of EtOH self-administration (operant), decreases the rate of extinction of EtOH self-administration, enhances relapse drinking, and enhances the ability of a priming dose of EtOH to increase EtOH-seeking (Rodd-Henricks et al., 2002a). These effects of
adolescent EtOH consumption in P rats were not observed in adult P rats given similar drinking exposure (Rodd-Henricks et al., 2002b). The current data is the first reported evidence that peri-adolescent EtOH consumption can increase adult EtOH self-infusions directly into a brain region that is a critical component of the neurocircuitry regulating drug reward.

In adults, chronic EtOH consumption (> 8 weeks) enhances the reinforcing properties of EtOH within the pVTA (Rodd et al., 2005b). Exposure to repeated cycles of EtOH access and deprivation (> 16 weeks of EtOH) further enhanced the alteration in the reinforcing properties of EtOH within the pVTA (Rodd et al., 2005c). The effects of adult EtOH consumption on the ability of EtOH microinjected into the pVTA to stimulate DA release in the AcbSh have not been examined. However, neuroadaptations produced by peri-adolescent EtOH consumption may not be identical to that observed following chronic adult EtOH consumption, but the overall impact is similar. Future studies need to determine if these neuroadaptations are consistent or unique between peri-adolescent and adult EtOH consumption.

Adolescent exposure to EtOH has been shown to alter DA within the mesolimbic DA system. Multiple studies have indicated that systemic administration of EtOH during adolescence results in higher basal DA levels in the Acb (Badanich et al., 2007; Pascual et al., 2009). Comparable EtOH injections in adolescent and adult rats result in higher basal level of DA in the Acb in adolescent rats (Pascual et al., 2009). Adolescent EtOH consumption in P rats increases DA clearance without a change in the extracellular concentration of DA within the Acb, suggesting increased DA neurotransmission (Sahr et al., 2004). In addition, adolescent EtOH consumption in P rats enhances and prolongs DA release in the Acb (both shell and core were assessed) following systemic administration of EtOH during adulthood (Sahr et al., 2004). The current experiment did not empirically examine basal DA levels in the AcbSh (no-net-flux
protocol), but an estimate of basal DA levels indicate that adolescent drinkers had higher basal DA levels in the AcbSh (approximately 22%). Therefore, the significant percent of baseline enhancement of DA levels in the AcbSh following EtOH microinjection into the pVTA in adolescent EtOH drinkers was observed despite possible higher basal DA levels (Fig. 4). Similar to the findings of Sahr et al. (2004) with i.p. EtOH injections, the ability of pVTA EtOH to stimulate DA release in the Acb was prolonged following adolescent EtOH consumption. Therefore, adolescent EtOH consumption in P rats results in a prolonged DA response in the Acb following both systemic and pVTA exposure to EtOH during adulthood.

The majority of research examining the effects of adolescent EtOH exposure has centered on the amygdala and hippocampus (learning associated effects; c.f. Spear and Varlinskaya 2005; Gulley and Juraska, 2013). The biological basis of the neuroadaptations in the pVTA produced by EtOH consumption during adolescence in the P rat was not directly examined in the current experiments. The data indicate 3 possibly distinct neuroadaptations (increased sensitivity to EtOH reinforcement in pVTA, increased pVTA DA neuronal response to EtOH, and a prolonged effect of EtOH on pVTA DA neurons) produced by adolescent EtOH consumption in the pVTA, which may involve unique, non-overlapping neuronal systems. EtOH self-infusion directly into the pVTA requires DA neuronal activity (Rodd et al., 2004) and can be reduced by co-administration of 5HT3 receptor antagonists (Rodd et al., 2005). It is possible that these systems may be altered by adolescent EtOH consumption, or exposure to other drugs of abuse during adolescence. Adolescent exposure to amphetamine (PND 30 to PND 50) results in an increase in basal firing rates of VTA DA neurons and 5HT neurons in the dorsal raphe (Labonte et al., 2012). Comparable experiments have not been conducted with EtOH.
Overall, the data indicate that adolescent EtOH consumption in the P rat, a rodent model of alcoholism, produced persistent alterations in the drug reward pathway that is indicative of increased sensitivity to EtOH and a potentiated/prolonged response to EtOH. The increase in reward sensitivity during adulthood following adolescent EtOH consumption maybe the biological basis for the deleterious effects that adolescent alcohol consumption has on adult alcoholism. Elucidating specific neuroadaptations within the mesolimbic DA system produced by adolescent EtOH consumption could lead to interventions/treatments to counter the consequences of this common human behavior.
Acknowledgements

The experiments were supported by grants obtain from the National Institute of Alcohol Abuse and Alcoholism Grants [AA07611], [AA07462], [AA012262], [AA020396] and [AA013522]
Authors Contribution

Participated in research design: Toalston, Bell, Murphy, McBride, and Rodd

Conducted experiments: Toalston, Deehan, Hauser, Engleman, Truitt, and Rodd

Performed data analysis: Toalston and Rodd

Wrote or contributed to the writing of the manuscript: Toalston, McBride, and Rodd
References


Gilpin NW, Karanikas CA, Richardson HN (2012) Adolescent binge drinking leads to changes in alcohol drinking, anxiety, and amygdalar corticotropin releasing factor cells in adulthood in male rats. PLoSOne 7:e31466.


Rodd ZA, Bell RL, McQueen VK, Davids MR, Hsu CC, Murphy JM, Li TK, Lumeng L, McBride WJ (2005c) Prolonged increase in the sensitivity of the posterior ventral tegmental area to the reinforcing effects of ethanol following repeated exposure to cycles of ethanol access and deprivation. J Pharmacol Exp Ther 315: 648-57.


Figure Legends

Figure 1. Depicts the mean (+ SEM) average number of infusions self-administered directly into the pVTA during sessions 1-4 in adolescent naïve subjects (left panel), and adolescent drinkers (right panel). * indicates significantly more infusions than aCSF controls. + indicates significantly more infusions than aCSF controls and corresponding adolescent naïve group. ^ indicates significantly more infusions than aCSF controls and 50 mg% group (adolescent naïve - n = 6-10/group; adolescent drinkers - n = 7-10/group).

Figure 2. Depicts the mean (+ SEM) number of lever responses in adolescent naïve subjects (left panels) and adolescent drinkers (right panels) given aCSF (top panels), 50 mg% (middle panels) or 75 mg% EtOH (bottom panels) to self-administer directly into the posterior VTA. * indicates significantly more responding on the active lever than that observed in aCSF controls or 50 mg% groups and discrimination between levers.

Figure 3. Depicts the mean (+ SEM) number of lever responses in adolescent naïve subjects (left panels) and adolescent drinkers (right panels) given 100 mg% (top panels) or 150 mg% EtOH (bottom panels) to self-administer directly into the posterior VTA. * indicates significantly more responding on the active lever than that observed in aCSF controls and discrimination between levers. + indicates significantly more responding on the active lever than that observed in aCSF controls, discrimination between levers, and significantly more responding in the adolescent drinkers than adolescent naïve rats.

Figure 4. Depicts the mean (+ SEM) percent change in DA levels in the AcbSh in adolescent naïve subjects (top panel) adolescent drinkers (right panels) given 0, 50, 75, 100 or 150 mg%
EtOH microinjected directly into the pVTA. * indicates significantly higher level of DA in the AcbSh of 150 mg% group compared to all other groups. + indicates significantly higher level of DA in the AcbSh of 75, 100, and 150 mg% group compared to aCSF and 50 mg% EtOH and 100 and 150 mg% adolescent drinkers are significantly higher than adolescent naïve rats. ^ indicates significantly higher level of DA in the AcbSh of 100 and 150 mg% group compared to aCSF and 50 mg% EtOH (adolescent naïve - n = 6-10/group; adolescent EtOH drinkers - n = 6-9/group).
Figure 1
**Figure 2**

The figure illustrates the lever responses of Naive and Drinkers groups across different conditions and sessions.

- **Naive Group**
  - Active and Inactive conditions are compared under aCSF and 50 mg% conditions.
  - Sessions 1 to 7 are depicted with data points showing trends in lever responses.

- **Drinkers Group**
  - Similar conditions and sessions are observed as in the Naive group.
  - Data points with * indicate significance differences compared to baseline.

The graph visually represents the changes in lever responses across sessions, indicating potential differences in behavior under different conditions.
Figure 4

**Naive**

- aCSF
- 50 mg%
- 75 mg%
- 100 mg%
- 150 mg%

**Drinkers**

- 10 min Inject

**Time**

Base1, Base2, Base3, Inj, Inj15, Inj30, Inj45, Inj60, Inj75, Inj90, Inj105, Inj120