5-HT_{1A} Autoreceptor Levels Determine Vulnerability to Stress and Response to Antidepressants


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SUMMARY

Most depressed patients don’t respond to their first drug treatment, and the reasons for this treatment resistance remain enigmatic. Human studies implicate a polymorphism in the promoter of the serotonin-1A (5-HT_{1A}) receptor gene in increased susceptibility to depression and decreased treatment response. Here we develop a new strategy to manipulate 5-HT_{1A} autoreceptors in raphe nuclei without affecting 5-HT_{1A} heteroreceptors, generating mice with higher (1A-High) or lower (1A-Low) autoreceptor levels. We show that this robustly affects raphe firing rates, but has no effect on either basal forebrain serotonin levels or conflict-anxiety measures. However, compared to 1A-Low mice, 1A-High mice show a blunted physiological response to acute stress, increased behavioral despair, and no behavioral response to antidepressant, modeling patients with the 5-HT_{1A} risk allele. Furthermore, reducing 5-HT_{1A} autoreceptor levels prior to antidepressant treatment is sufficient to convert nonresponders into responders. These results establish a causal relationship between 5-HT_{1A} autoreceptor levels, resilience under stress, and response to antidepressants.

INTRODUCTION

Depression is one of the leading public health problems in the world today and antidepressants are among the most commonly prescribed medications (National Center for Health Statistics, 2007). Current evidence suggests that depressive disorders are precipitated by stressful life events, interacting with genetic and other predisposing factors (Caspi et al., 2003; Fava and Kendler, 2000; Leonardo and Hen, 2006). The response to antidepressants, like the response to external stressors, is variable, and fewer than half of depressed patients respond to their first drug treatment, leading to prolonged suffering and increased medical costs (Rush et al., 2006). Elucidating the exact nature of both the factors predisposing to depression and the mechanisms underlying treatment resistance remains an important and unmet need.

The serotonergic system modulates the acute stress response and has been implicated in both the etiology of depression and anxiety as well as the response to treatment (Holmes, 2008; Lanfumey et al., 2008). Most drugs used for treating depression increase serotonin levels, including the most commonly used drugs, the selective serotonin reuptake inhibitors (SSRIs), which are effective at treating both anxiety and depression (Schatzberg and Nemeroff, 2009). Serotonin is released from serotonergic neurons, which have cell bodies localized in the mid-brain raphe nuclei but send axonal projections throughout the brain, where released serotonin impacts a diverse group of serotonin receptors.

The serotonin-1A (5-HT_{1A}) receptor is an inhibitory G protein-coupled receptor expressed both in serotonergic neurons (as an autoreceptor), where it controls serotonergic tone through feedback inhibition, and in target areas receiving serotonergic innervation (as a heteroreceptor) (Beck et al., 1992; Hamon et al., 1990; Riad et al., 2000). Thus, it has the dual ability to modulate both global serotonin levels and local responses to released serotonin. The role of 5-HT_{1A} autoreceptors in controlling serotonergic tone has led to the hypothesis that these receptors delay the therapeutic action of SSRIs and other drugs that act by increasing serotonin levels (Gardier et al., 1996). Specifically, 5-HT_{1A} autoreceptors exert negative feedback inhibition in response to increased serotonin; thus, progressive autoreceptor desensitization may be responsible for the delayed onset of action of these drugs (Blier et al., 1998).

Genetic and imaging studies in humans have suggested that differences in 5-HT_{1A} receptor levels or regulation are also associated with depression, anxiety, and the response to antidepressants (Le François et al., 2008; Lesch and Gutknecht, 2004; Strobel et al., 2003). Most recently, an association has been reported between a C(-1019)G polymorphism in the promoter...
region of the Htr1a gene and a number of mood-related variables, including depression, the response to antidepressant treatment, and amygdala reactivity (Fakra et al., 2009; Le François et al., 2008). Although initial reports suggested that this polymorphism might control autoreceptor levels without impacting heteroreceptor levels (Lemonde et al., 2003), recent imaging findings suggest that 5-HT1A auto- and heteroreceptors are both affected (Parsley et al., 2006). Thus, despite significant attention and interest regarding the role of the 5-HT1A autoreceptors in the treatment and etiology of depression, a direct test of their involvement has remained beyond the reach of available techniques.

Studies in mice have suggested that 5-HT1A receptors are generally involved in modulating both anxiety and depression-related behavior (Heisler et al., 1998; Klemenhagen et al., 2006; Parks et al., 1998; Ramboz et al., 1998), but have not usually distinguished between auto- and heteroreceptors. 5-HT1A knockout (KO) mice (lacking the receptor everywhere, throughout life) display a robust anxiety-like phenotype in conflict-anxiety paradigms, while exhibiting decreased behavioral despair in response to stress (Heisler et al., 1998; Parks et al., 1998; Ramboz et al., 1998). Because behavioral despair in response to stress is decreased by acute treatment with a number of drugs used to treat depression, this phenotype has often been referred to as “antidepressed.” However, anxiety and other stress-related disorders such as depression are often co-morbid in humans (Kendler et al., 1992), making the combination of an anxious phenotype with an antidepressed phenotype in 5-HT1A KO mice difficult to interpret. Subsequently, the antidepressed phenotype of mice lacking the 5-HT1A receptor has been largely ignored.

Overall, the role of 5-HT1A auto- versus heteroreceptors in determining the response to stress, the anxiety phenotype, or the response to treatment with antidepressants has not been adequately addressed. Both pharmacological approaches and genetic animal models have been hampered by the difficulty in separating effects on autoreceptors from effects on heteroreceptors. To directly test the role of 5-HT1A autoreceptors in anxiety, depression, and the response to antidepressants, we first developed a novel system capable of suppressing expression of 5-HT1A receptors in a tissue-specific and temporally specific manner. We used this system to examine the biological consequences of altering autoreceptor levels without affecting heteroreceptor levels. Specifically, we tested the hypothesis that altering autoreceptor levels may result in differences in anxiety, stress response, depression, or response to antidepressants.

RESULTS

Conditional Suppression of the 5-HT1A Receptor

In order to generate mice in which we could conditionally suppress 5-HT1A receptors, we crossed mice containing two distinct engineered alleles. The first is a knockin of the tetracycline operator (tetO) into the promoter region of the murine Htr1a gene, to create the Htr1a<sup>tTS</sup> allele. The second is a transgene expressing the tetracycline-dependent transcriptional suppressor (tTS) under the control of the β-actin promoter (Figure 1A) (Mallo et al., 2003). Insertion of the tetO element into the endogenous Htr1a locus does not interfere with normal 5-HT1A receptor expression patterns (Audero et al., 2008). tTS suppresses endogenous expression of the 5-HT1A receptor by binding to tetO in a doxycycline-dependent manner (Figure 1A) (Mallo et al., 2003). Maintenance of mice on doxycycline prevents the tTS protein from binding the tetO sequence and results in unimpeded expression of the 5-HT1A receptor.

Since previous studies of the 5-HT1A receptor have suggested that the receptor is involved in the developmental establishment of anxiety-like behavior (Gross et al., 2002; Lo Iacono and Gross, 2008), a key goal of this system was achieving inducible suppression in adulthood, in order to distinguish between developmental and adult effects of lacking the receptor. We found that withdrawal of doxycycline allows binding of tTS to the tetO sequence and progressive suppression of 5-HT1A receptor levels. Four weeks after doxycycline removal, maximal suppression is achieved and 5-HT1A receptor levels are undetectable by 125<sup>I</sup>MPPI autoradiography, revealing a half-life of receptor disappearance of approximately 8 days (Figure S1A, available online).

Raphe-Specific Suppression of 5-HT1A Receptors

Having established the feasibility of inducible suppression of 5-HT1A receptors in the brain, we created a mouse in which we could specifically modulate 5-HT1A autoreceptor levels in serotonergic raphe neurons without affecting heteroreceptor levels. We accomplished this by generating a mouse with raphe-specific expression of tTS under the control of the previously characterized 540Z Pet-1 promoter fragment (Pet1-tTS) (Fisher et al., 2006) (Figure 1B). We crossed these Pet1-tTS mice with the Htr1a<sup><sup>dup/cherO</sup></sup> mice described above. In the presence of doxycycline, mice homozygous for the Htr1a<sup><sup>dup/cherO</sup></sup> allele and possessing one copy of the Pet1-tTS transgene display levels of 5-HT1A autoreceptor that are indistinguishable from littermates lacking the tTS transgene (1A-High) (Figure S1B). Removal of doxycycline at postnatal day 50 for 4 weeks creates a population of adult animals with lower expression of 5-HT1A autoreceptors (1A-Low) (Figure 1C).

Quantitative autoradiography in the raphe and selected forebrain structures (entorhinal cortex, amygdala, and ventral dentate gyrus) demonstrates that, compared to 1A-High mice, 1A-Low mice have indistinguishable levels of 5-HT1A heteroreceptor expression (Figure S1C), but display about 30% less autoreceptor expression than 1A-High mice (Figure 1D). Similar differences are seen in both the dorsal and median raphe (dorsal raphe one tailed t test, t<sub>14</sub> = 2.965, p = 0.005; median raphe one tailed t test, t<sub>14</sub> = 1.967, p = 0.041) (Figure 1E). An overall difference of 30% in autoreceptor levels is consistent with the range of receptor levels that are seen within human populations (Drevets et al., 2007).

Decreased Response to Agonist after Adult Suppression of 5-HT1A Autoreceptors

To directly confirm that the differences in 5-HT1A autoreceptor levels revealed by autoradiography had functional consequences, we performed whole cell recordings in the dorsal raphe and measured the response to the 5-HT<sub>1A</sub> agonist...
5-carboxyamidotryptamine (5-CT) (Figure 2A). After recording, we confirmed that neurons were serotonergic by filling recorded neurons with biocytin and performing immunohistochemistry for biocytin and TPH (Figure 2C). We observed a significantly higher average current elicited by agonist challenge in the serotonergic neurons of 1A-High mice versus 1A-Low mice (two-tailed Mann-Whitney test, U = 104.0; p = 0.0008) (Figure 2B). Much of this difference resulted from a significant proportion of neurons in the 1A-Low mice that fail to respond to the agonist challenge (defined by current <5 pA) (c^2 = 15.914; p < 0.0001) (Table S1). These data suggest that the tTS-mediated transcriptional suppression in the 1A-Low mice results in a mosaic population of serotonergic neurons, some of which retain full responsiveness to 5-HT1A agonists while others are no longer responsive. The reasons for this mosaicism are unclear; it may represent all-or-nothing genetic silencing as a result of variable transgene expression. Alternately, it may arise secondarily as a result of further autoreceptor desensitization in some neurons with low levels of gene expression.

To independently assess the in vivo functional status of the 5-HT1A autoreceptors in 1A-High and 1A-Low mice, we examined their hypothermic response to 5-HT1A agonist challenge. While 1A-High mice display the expected dose-dependent hypothermic response to the 5-HT1A agonist, 8-OH-DPAT (repeated-measures two-way analysis of variance (ANOVA) with time as a within-subject factor and dose as a between-subject factor; main effect of dose F(2,12) = 61.689; p < 0.0001; post hoc between vehicle and 0.1 mg/kg, p = 0.0155; between vehicle and 0.5 mg/kg, p = 0.0001), 1A-Low mice displayed a markedly attenuated response, which was detected only at the higher dose (repeated-measures two-way ANOVA; main effect of dose F(2,11) = 6.109; p = 0.0164; post hoc between vehicle and 0.5 mg/kg, p = 0.0113) (Figure 2D). These findings are consistent with previous literature indicating that the 5-HT1A autoreceptors are responsible for the hypothermic effect of 8-OH DPAT in the mouse (Martin et al., 1992). In summary, our results demonstrate that a modest difference in autoreceptor expression between 1A-High and 1A-Low mice results in robust differences in their response to agonist treatment both in vitro and in vivo.

**Increased Spontaneous Activity of Serotonergic Neurons Following Adult Autoreceptor Suppression**

To determine whether the functional differences in autoreceptor levels had an effect on overall serotonergic tone, we measured the firing rates of serotonergic dorsal raphe neurons in an in vivo anesthetized preparation. Neurons were included in the analysis based on the characteristics of their action potentials, and averaged traces of these action potentials are shown as insets (Figure 3) (Vandermaelen and Aghajanian, 1983). We observed significantly different distributions of firing rates between the groups (two-tailed Mann Whitney test, U = 104; p = 0.0057), with raphe neurons from 1A-Low mice more likely to fire at higher rates (5.5 ± 0.8 Hz) than the 1A-High mice.
(2.6 ± 0.6 Hz) (two-tailed t test for group, T<sub>39</sub> = 2.874; p = 0.0065). This overall firing rate increase demonstrates higher serotonergic tone in 1A-Low mice, consistent with decreased autoinhibition.

**Decreasing Autoinhibition in Adult Animals Does Not Change Baseline Anxiety Measures**

Complete 5-HT<sub>1A</sub> KO mice, lacking both auto- and heteroreceptors throughout life, have consistently shown increased anxiety in conflict-based tasks (Heisler et al., 1998; Klemenhagen et al., 2006; Parks et al., 1998; Ramboz et al., 1998). To test whether specifically modulating 5-HT<sub>1A</sub> autoreceptors in adulthood impacts anxiety-like behavior, we tested our mice in two conflict-based tests: the open field paradigm and the light/dark choice test. 1A-High and 1A-Low mice displayed no difference in either total exploration (two-way repeated-measures ANOVA with time as a within-subject factor and genotype as a between-subject factor; F<sub>1,40</sub> = 0.583; p = 0.45) or exploration in the center of the open field (two-way repeated measures ANOVA, F<sub>1,40</sub> = 0.249; p = 0.521) (Figure 4A). These data directly demonstrate that changes in adult levels of 5-HT<sub>1A</sub> autoreceptors do not alter anxiety-like behavior, consistent with previous findings suggesting a developmental role for 5-HT<sub>1A</sub> receptors in the establishment of anxiety-related circuitry (Gross et al., 2002; Lo Iacono and Gross, 2008).

**Decreased Autoinhibition in Adulthood Alters Response to Stress**

Studies in humans suggest that 5-HT<sub>1A</sub> receptor levels might influence behavioral resilience to stressful situations, with high expressors being more susceptible to depression than low expressors (Anttila et al., 2007; Kraus et al., 2007; Lemone et al., 2003; Neff et al., 2009). Moreover, 5-HT<sub>1A</sub> KO mice display increased physiological responses to acute stress (Van Bogaert et al., 2006). To assess whether altering serotonergic autoinhibition is sufficient to alter stress responsivity, we examined the response of 1A-High and 1A-Low mice in the stress-induced hyperthermia paradigm (Adriaan Bouwknecht et al., 2007). This paradigm measures one of the acute physiological responses to stress, namely that body temperature is increased as a result of autonomic system arousal. Hyperthermia in this paradigm correlates with measures of HPA axis reactivity, such as corticosterone, ACTH, and glucose plasma levels, and other measures of autonomic reactivity, such as heart rate (Graenenink et al., 1994). In this test, the 1A-Low mice displayed a more robust autonomic response to an acute stressor compared to 1A-High mice (ANOVA, F<sub>1,20</sub> = 43.201, p < 0.0001) (Figure 4C).

Having observed a difference in a physiological response to acute stress, we next examined the behavioral response of these
animals in two distinct stress-related paradigms: the tail suspension test and the forced swim test. In both tests, immobility is scored as a measure of behavioral despair (Lucki, 1997). No difference between groups was detected in the tail suspension test ($F_{1,49} = 0.001, p = 0.9735$) (Figure 4D). In the forced swim test, animals were exposed to the stressor twice over a 24 hr period and the last 4 min of a 6 min session was scored on each day. Unlike the tail suspension test where periods of immobility appear early and occur in brief bouts throughout the duration of the test, in the forced swim test, animals are initially fairly active with immobility generally emerging in the third minute of the test (Buccafusco, 2009; Cryan et al., 2005; Porritt et al., 1977). 1A-High and 1A-Low mice responded indistinguishably to the initial stressor on day 1 and both groups showed the expected decrease in mobility on day 2. However, 1A-High, but not 1A-Low mice, displayed progressively less mobility or more behavioral despair, upon reexposure the second day (Figure 4E) (repeated-measures ANOVA, group by time interaction, $F_{3,43} = 4.535, p = 0.0047$), consistent with prior results demonstrating the need for repeated exposure to uncover effects of serotonergic manipulations (Ramboz et al., 1998; Wellman et al., 2007). Moreover, the mobility of the 1A-Low mice appears to be higher than 1A-High mice during the final 2 min of the test, suggesting a different adaptation to stress over time in the two groups (ANOVA, between group minutes 5–6, $F_{1,41} = 3.953, p = 0.0535$) (Figure 4E). Thus, while decreasing adult levels of 5-HT$_{1A}$ autoreceptors does not alter either conflict-based anxiety (Figures 4A and 4B) or the behavioral response to an acute stressor (Figures 4D and 4E), decreasing adult autoreceptor levels results in increased physiological reactivity to stress (Figure 4C) and appears to elicit a more active response to a repeated stress in a depression-related task (Figure 4E).

To further test the possibility that 1A-High and 1A-Low mice differed in their behavioral sensitivity to repeated stress, we subjected animals to a repeated daily mild stressor, oral gavage, for 4 weeks (28 days). This manipulation has been shown to increase stress-response measures in rodents, such as circulating corticosterone, body temperature, and heart rate (Dalm et al., 2008). Following 4 weeks of repeated stress, 1A-High and 1A-Low mice remained indistinguishable in their total exploration in the open field (two-way repeated measures ANOVA, $F_{1,25} = 0.003, p = 0.9586$) (Figure 5A) and in time spent in the center of the open field (ANOVA, $F_{1,25} = 1.587, p = 0.2195$) (data not shown) and retained their distinct physiological reactivity to stress as assessed by the SIH test (one tailed $t$ test, $t_{10} = 2.057, p = 0.0334$) (Figure 5B). However, following repeated mild stress, 1A-High, but not 1A-Low mice, displayed decreased mobility over time on the first day (day 1) of the forced swim test (paired $t$ test for 1A-High group over time $t_{13} = 3.482, p = 0.004$ paired $t$ test for 1A-Low group over time $t_{13} = -0.276, p = 0.7872$) (Figure 5D), a result that had only been observed after repeated (two-day) swim stress previously (Figure 4C). Moreover, following 4 weeks of repeated stress, 1A-High mice displayed significantly less mobility in the tail-suspension test, compared
to 1A-Low mice (F(1,25) = 4.478, p = 0.0445) (Figure 5C). This difference emerged only after a repeated mild stressor (Figure 4D). Overall, these results are consistent with a differential susceptibility to stress between the two groups of animals, as measured by behavioral responses in depression-related stress paradigms.

**Decreased Autoinhibition Alters Behavioral Response to Fluoxetine**

Having demonstrated that decreased serotonergic autoinhibition yielded a consistent difference in responsiveness to stress, we asked whether such a change might also be sufficient to impact responsiveness to antidepressant drugs. To directly test whether the behavioral response to antidepressant treatment is affected by autoreceptor levels, we chose the novelty suppressed feeding (NSF) paradigm (Bodnoff et al., 1988; Gross et al., 2000; Santarelli et al., 2003). This paradigm has two features that make it useful to model the variable human response to antidepressants: (1) like many behavioral tests, the response is affected by the genetic background of the mice (Lucki et al., 2001), with some strains not responding to SSRIs in this paradigm (Ibarguen-Vargas et al., 2008); and (2) unlike other commonly used tests of antidepressant response, such as the tail suspension test or the forced swim test, the NSF is sensitive to chronic (>3 weeks) but not acute or subchronic (<10 days) treatment with antidepressant drugs (Dulawa and Hen, 2005; Lira et al., 2003; Wang et al., 2008). Thus, by testing the response to fluoxetine in this paradigm we can model both the time frame required for response to treatment and the factors that mediate treatment response.

We administered fluoxetine or vehicle to 1A-High and 1A-Low mice and tested them in the NSF paradigm, a test of hypophagia that measures the latency of a mouse to consume food placed in the middle of a brightly lit, aversive arena (Bodnoff et al., 1988; Gross et al., 2000; Santarelli et al., 2003). Following a chronic, 26 day treatment with fluoxetine, we observed that 1A-Low mice respond robustly, as shown by their lower latency to feed relative to their vehicle-treated controls (p = 0.0031 by Mantel-Cox log rank test) (Figure 6D). However, no response to fluoxetine was observed in the 1A-High mice (p = 0.8475 by Mantel-Cox log rank test) (Figure 6C). Thus, like many mouse strains, the 1A-High mice do not respond to fluoxetine in this paradigm. Furthermore, this experiment establishes a causal relationship between 5-HT1A autoreceptor levels and response to antidepressants; namely, a decrease in 5-HT1A autoreceptor levels in adulthood, prior to antidepressant treatment, is sufficient to confer responsiveness to fluoxetine in an otherwise treatment-resistant population.

To determine whether autoreceptors might determine time to response, we also examined the response of both 1A-High and 1A-Low mice to subchronic (8 day) treatment with fluoxetine. Under these conditions, 1A-Low mice show a robust response to fluoxetine (p = 0.011 by Mantel-Cox log rank test), while no such response is seen in the 1A-High mice (p = 0.2343 by Mantel-Cox log rank test) (Figures 6A and 6B). This result suggests that decreased autoreceptor function may permit an early response to treatment, consistent with the hypothesis that feedback inhibition by 5-HT1A autoreceptors delays the onset of response by limiting the initial increase in serotonin (Artigas et al., 1996).

**Serotonin Levels in 1A-High and 1A-Low Mice Are Indistinguishable at Baseline, but Differ Significantly in Response to Fluoxetine Challenge**

Having observed behavioral differences between 1A-High and 1A-Low mice in response to challenge with both repeated stress and serotonin transporter blockade, we next asked how these differences were reflected at the neurochemical level. We performed in vivo microdialysis in two representative forebrain areas: the ventral hippocampus (vHPC) and the prefrontal cortex (PFC). Despite the differences in basal raphe firing, no difference was detected in serotonin levels at baseline between the groups in either the vHPC or PFC (two-way ANOVA for brain region and

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**Figure 5. 1A-High Mice Display a Less Active Behavioral Response in Stressful Paradigms Following a Repeated Mild Stressor**

Following 4 weeks of a daily mild stressor, 1A-High and 1A-Low mice displayed indistinguishable behavior in the open field paradigm (A) (n = 13–14 mice/group). 1A-Low mice retained a more robust increase in response to novel cage stress (B) (n = 6/group; *p < 0.05), similar to naive mice. However, after repeated stress, 1A-High mice displayed less mobility than 1A-Low mice in the tail suspension test (C) (n = 13–14 mice/group; *p = 0.0445) and less mobility over time in a single exposure to the forced swim test (D) (n = 13–14 mice/group; **p = 0.004). Values are mean ± SEM.

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**Figure 6. Behavior of 1A-High and 1A-Low Mice as a Function of Fluoxetine Treatment**

Panel A shows the mean ± SEM total path length (cm) over the first 30 minutes of the NSF test. 1A-High mice displayed less mobility than 1A-Low mice (p = 0.004). Values are mean ± SEM. Panel B shows the mean ± SEM core temperature (°C) over the first 10 minutes of the NSF test. 1A-Low mice displayed less mobility than 1A-High mice (p = 0.004). Values are mean ± SEM. Panel C shows the mean ± SEM % mobility over time in the open field paradigm. *p = 0.0445. Values are mean ± SEM. Panel D shows the mean ± SEM % mobility over time in the open field paradigm. **p = 0.004. Values are mean ± SEM.
group, main effect of group, F_{1,26} = 0.006, p = 0.937) (Table 1). Following 8 days of fluoxetine treatment, we observed a difference in serotonin levels in the vHPC, with higher levels of serotonin in the 1A-Low animals (two-way ANOVA for brain region and group, main effect of group, F_{1,22} = 9.705; p = 0.005; region by group interaction, F_{1,22} = 8.977; p = 0.0067; post hoc for group in the vHPC, p = 0.003). Interestingly, serotonin levels continued to increase in both groups with chronic fluoxetine treatment. Differences in extracellular serotonin levels were normalized between the groups by 26 days of fluoxetine treatment, in both forebrain areas measured (two-way ANOVA for brain region and group, main effect of group, F_{1,24} = 0.202, p = 0.657).

To further dissect the neurochemical effects of fluoxetine on mice with different levels of serotonergic autoinhibition, we assessed changes in serotonin levels in response to an acute challenge with fluoxetine or saline. Both groups of mice displayed significant increases in serotonin in response to acute fluoxetine treatment compared to saline in both the vHPC (Figures 7A and 7B) (two-way ANOVA, main effect of group, F_{1,26} = 4.352, p = 0.0469; main effect of treatment, F_{1,26} = 37.822, p < 0.0001; group by treatment interaction, F_{1,26} = 4.512, p = 0.0433; post hoc for treatment in 1A-High mice, p < 0.0001; post hoc for treatment in 1A-Low mice, p = 0.0042) and the HPC.

PFC (Figures 7C and 7D) (two-way ANOVA, main effect of group, F_{1,26} = 6.769, p = 0.0151; main effect of treatment, F_{1,26} = 23.880, p < 0.0001; post hoc for treatment in 1A-High mice, p < 0.0065; post hoc for treatment in 1A-Low mice, p = 0.0039). However, 1A-Low mice displayed a larger increase in 5-HT in response to fluoxetine in both brain regions (post hoc for group in fluoxetine-treated animals in the PFC, p = 0.0474; post hoc for group in fluoxetine-treated animals in the vHPC, p = 0.0474). Thus, to ensure that the lack of behavioral response to fluoxetine in 1A-High mice was not due to a failure of autoreceptor desensitization, we assessed the animals’ hypothermic response to 8-OH-DPAT after chronic fluoxetine treatment. While 1A-High mice treated chronically with vehicle displayed a robust hypothermic response to 8-OH-DPAT challenge (repeated-measures ANOVA, main effect of dose F_{1,6} = 35.477, p = 0.001; dose by time interaction F_{1,5} = 5.080, p = 0.0017), 1A-High mice treated chronically with fluoxetine no longer responded to 8-OH-DPAT challenge (repeated-measures ANOVA, main effect of dose F_{1,6} = 0.085, p = 0.781; dose by time interaction F_{1,5} = 1.479, p = 0.226) (Figure 8A). This result is in agreement with previous reports showing desensitization of 5-HT_1A autoreceptors following chronic treatment with a number of drugs used to treat 5-HT_1A autoreceptors: Stress and Treatment Response

| Table 1. Serotonin Levels Measured by In Vivo Microdialysis in 1A-High and 1A-Low Mice Treated with Fluoxetine |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                | HPC             | PFC             | HPC             | PFC             |
| **1A-High**                     | 2.6 ± 0.2       | 2.2 ± 0.4       | 3.1 ± 0.3       | 2.4 ± 0.5       |
| **1A-Low**                      | 2.7 ± 0.4       | 2.1 ± 0.4       | 6.8 ± 0.9**     | 2.5 ± 0.4       |

Mean basal serotonin levels (fmol/20 μl dialysate) ± SEM in ventral hippocampus (HPC) and prefrontal cortex (PFC). **p < 0.01 compared to 1A-High in HPC.
depression, including SSRIs (Blier et al., 1998). A similarly attenuated response to 8-OH-DPAT challenge is seen in 1A-Low mice treated chronically with both vehicle (two-way repeated-measures ANOVA, main effect of dose $F_{1,6} = 1.252, p = 0.306$; dose by time interaction $F_{1,5} = 2.831, p = 0.0328$) and fluoxetine (repeated-measures ANOVA, main effect of dose $F_{1,6} = 0.922, p = 0.374$; dose by time interaction $F_{1,5} = 3.537, p = 0.0124$) (Figure 8B), consistent with the blunted response we observed previously in these animals (Figure 2D). Therefore these results suggest that desensitization of 5-HT$_{1A}$ autoreceptors alone is not sufficient for the behavioral response to fluoxetine, but rather that 5-HT$_{1A}$-mediated serotonergic tone prior to treatment is critical for establishing treatment response.

**DISCUSSION**

**tetO-Based Gene Suppression**

Conditional KO and transgenic mice are powerful tools for probing the behavioral roles of genes expressed in the brain. In practice, however, most approaches have been limited by ectopic expression, lack of temporal control, or irreversibility.

These weaknesses are largely overcome in the system presented here. We use an adaptation of the tetO-inducible strategy that relies on insertion of tetO sites into the endogenous promoter of a gene of interest. In the case of the Htr1a tetO/tetO mice used here, this insertion is largely silent (i.e., does not noticeably alter the pattern of 5-HT1A receptor expression) in the absence of tTS. We have now successfully generated silent...
tetO insertions in several other genes (data not shown), suggesting that this strategy is broadly generalizable. Expression of the 5-HT$_{1A}$ receptor in this system is tightly suppressed by a ubiquitously expressed tTS binding to tetO sequences that are knocked in to the endogenous Htr1a locus. Importantly, suppression can be achieved at any point in the life of the animal by withdrawing doxycycline. Furthermore, specificity of gene suppression is dictated by an overlap between transgenic tTS expression patterns and endogenous expression of the gene. This ensures that tTS-mediated suppression only occurs in cells that normally express the gene of interest, eliminating the possibility for ectopic gene expression. Finally, another advantage of this system is that, unlike systems that rely on genetic recombination, suppression can be reversed in the presence of doxycycline (data not shown).

**Modeling the Human Htr1a C$(-1019)$G Polymorphism**

Our 1A-High and 1A-Low mice provide a mechanistic model of one of the predicted consequences of the recently identified human Htr1a C$(-1019)$G polymorphism: namely, that it results in differential transcriptional suppression of the Htr1a gene in serotonergic neurons and creates populations of individuals with higher and lower expression of 5-HT$_{1A}$ autoreceptors. Initial in vitro characterization of expression driven off this polymorphic allele revealed preferential suppression of the C-allele by several transcription factors in a raphe-derived cell line, but not in cell lines derived from other brain areas. This suggested that C carriers might express lower levels of 5-HT$_{1A}$ autoreceptor than G-carriers (Lemonde et al., 2003). However, the only subsequent binding study to report an association between the G-allele and increased 5-HT$_{1A}$ receptor binding reported increases in both the raphe and other brain regions (Parsey et al., 2006). It remains unclear whether the human polymorphism directly affects 5-HT$_{1A}$ gene expression throughout the brain or whether the changes in forebrain levels are a secondary consequence of a primary change in autoreceptors.

**Consequences of Decreased 5-HT$_{1A}$ Autoreceptor Levels in Adulthood**

Our data from 1A-High and 1A-Low mice provides the first direct evidence for a functional model incorporating the predictions generated from both preclinical and clinical studies, including the recent human Htr1a C$(-1019)$G polymorphism studies (Albert and Lemonde, 2004; Lesch and Gutknecht, 2004). In this model, 5-HT$_{1A}$ autoreceptor-modulated intrinsic raphe firing rates are directly related to resilience under stress and to the response to antidepressant treatment, demonstrated here with the prototypical SSRI fluoxetine (Figure 9). In such a model, when the serotonergic system is activated, higher intrinsic 5-HT$_{1A}$ autoreceptor levels (either in 1A-High mice or G/G individuals) results in lower raphe firing rate and lower intrinsic 5-HT$_{1A}$ autoreceptor (in 1A-Low mice or C/C individuals) results in higher raphe firing rate. The increased raphe firing rate (in 1A-Low mice or C/C individuals) would increase resilience to chronic stress by increasing serotonin release throughout the brain upon challenge, as seen by the decreased behavioral despair of 1A-Low mice following stress. Interestingly, our data suggests that at baseline (i.e., non-stressful conditions), levels of serotonin do not differ between the 1A-High and 1A-Low mice.

Studies in rats treated chronically with SSRIs have shown an initial decrease of raphe firing at the beginning of treatment, with firing rates recovering to baseline following chronic treatment and 5-HT$_{1A}$ autoreceptor desensitization (Blier et al., 1998). Thus, in the presence of an SSRI, we expect 5-HT$_{1A}$ autoreceptor-mediated inhibition of raphe firing to occur in both 1A-High and 1A-Low animals, albeit to different extents. Indeed, 1A-Low animals display faster increases in extracellular serotonin in the hippocampus upon repeated (8 day) fluoxetine treatment, directly reflecting differential autoinhibition in response to reuptake blockade. Interestingly, extracellular serotonin levels reach a similar plateau in both 1A-High and 1A-Low animals following chronic (26 day) treatment and autoreceptor desensitization, demonstrating that the behavioral differences between the groups cannot be fully explained by extracellular serotonin levels. Because our behavioral groups differ only by the levels of their 5-HT$_{1A}$ autoreceptors at the start of treatment, the differences in behavioral response to fluoxetine must be mediated by either differential downstream changes or subtler differences in serotonergic tone.

In summary, two of the main associations from studies of the C$(-1019)$G polymorphism in humans are recapitulated in our model: susceptibility to stress and response to antidepressant treatment. In addition, our data suggest that the effects of the polymorphism may be easier to detect under conditions of chronic stress or pharmacological intervention.

**Behavioral Dissociation and Treatment Implications**

Together with previous work, this study also establishes a double dissociation of 5-HT$_{1A}$ receptor function in baseline anxiety- and

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**Figure 9. Model of 5-HT$_{1A}$ Autoreceptor Effects on the Serotonergic Raphe**

Diagram depicts representative raphe neurons in 1A-High and 1A-Low animals, emphasizing the differences between the two groups. 1A-High mice have lower basal firing rate (indicated above the cell) and high levels of somatodendritic 5-HT$_{1A}$ autoreceptor, which exert robust inhibitory effects on raphe firing. This results in increased behavioral despair in response to stress, compared to 1A-Low mice. Conversely, 1A-Low mice have a higher basal firing rate and low levels of somatodendritic 5-HT$_{1A}$ autoreceptors, which exert less inhibitory control over raphe firing rates. This results in less behavioral despair in response to stress, compared to 1A-High mice. While 1A-High mice do not respond behaviorally to treatment with the antidepressant fluoxetine, 1A-Low mice display a robust behavioral response. 1A-High and 1A-Low mice provide a mechanistic model for humans carrying, respectively, the G/G and C/C alleles of the Htr1a C$(-1019)$G polymorphism.
transcriptional stop cassette from Htr1a	tetO KO mice by crossing to an HSP70-cre line that deletes in the germline (Dietrich et al., 2000; Gross et al., 2002). The resulting Htr1a	tetO mice contain a tetO-CMV promoter inserted 5′ of the Htr1a coding region and express the 5-HT1A autoreceptor in a pattern that is indistinguishable from the wild-type. β-actin tTS Htr1a	tetO mice were created by breeding mice with TS expressed under the control of a human β-actin transgene (Malo et al., 2003) onto a background homozygous for the Htr1a	tetO allele. Tg(Pet-1-tTS) was produced by cloning the coding sequence of Pet-1 into the T3 polylinker region of the NarI/BglII modification 5′ plasmid, placing a protein followed by an SV40 polyadenylation signal (Mallo et al., 2003). The Pet-1-tTS transgene was transmitted through the male germline, ensuring that all pups were raised by mothers of the same genotype, regardless of doxycycline status. All experiments were conducted on male offspring. Animals were maintained on a mixed 129Sv/SV; C57B6; CBA background.

**Pet-1-tTS** Htr1a	tetO mice and their Pet-1-tTS Htr1a	tetO littermates were fed chow containing 40 mg/kg doxycycline ( Bioserv) throughout development to prevent tTS-mediated transcriptional suppression of the 5-HT1A receptor. This chow was otherwise identical in composition to standard laboratory chow (described below). At 50 days postnatal, animals were randomly split into two groups; one continued receiving doxycycline chow (1A-High) and the other began receiving doxycycline-free standard laboratory chow (1A-Low) (Prolab Isopro RMH 3000; PMI Nutrition International). To control for the possible effects of doxycycline on behavior, littermate controls lacking the tTS transgene, in which doxycycline had no effect on 5-HT1A receptor expression, were also tested in baseline behavioral experiments (Figure S2).
(3 kHz to 30 Hz) with an LPF 200 DC Amplifier/Filter (Warner Instruments) and collected on-line using Clampex 10.1 software (Molecular Devices). A serotonin neuron was characterized by a biphasic action potential that was approximately 2 ms in duration. A stable baseline of spontaneous activity was recorded for at least 3 min. Multiple neurons per mouse were recorded through multiple descents. Only firing rates within two standard deviations of the mean were included in the analysis.

**Intracerebral In Vivo Microdialysis**

Mice were treated with fluoxetine for 0, 8, or 26 days, as indicated (18 mg/kg, p.o.). Extracellular 5-HT levels were measured by in vivo microdialysis as previously described (Guard et al., 2008). Briefly, after the last dose of fluoxetine, two concentric dialysis probes were implanted in the vHPC and PFC (outer diameter x active length: 0.3 x 1.6 and 0.3 mm x 2 mm, respectively) of anesthetized mice (chloral hydrate, 400 mg/kg, i.p.). Stereotoxic coordinates (mm) were as follows: PCF: A = 1.6, L = 1.3, V = 1.6; vHPC: A = 2.8, L = 3.0, V = 3.0 (Franklin and Paxinos, 1997). Animals were allowed to recover for a period of 24 hr. Following recovery, probes were continuously perfused with a CSF, and dialysate was collected every 15 min for analysis by HPLC amperometry (Guiard et al., 2008). Baseline 5-HT levels were calculated as the average of the first four samples, ± SEM. Freely moving mice were treated (t = 0) with either a challenge dose of fluoxetine (18 mg/kg; i.p.) or its vehicle, and dialysate samples were collected for a 0–120 min post-treatment period. The limit of sensitivity for 5-HT was 0.5 fmol/sample (signal-to-noise ratio 2). Following sample collection, brains were removed and sectioned to ensure proper probe placement.

**Behavioral and Physiological Testing**

All animals used for behavioral testing were age matched within 2 weeks. Animals were initially tested at 11–13 weeks of age, at least 4 weeks after the cessation of doxycycline in 1A-Low animals. Baseline anxiety tests were completed before other behavioral tests. Fluoxetine was given after baseline behavioral and physiological measures were assessed, at 18 mg/kg/day p.o. for up to 28 days. Testing in the NSF paradigm occurred on day 26 of treatment.

**8-OH DPAT-Induced Hypothermia**

Body temperature was assessed intrarectally, using a lubricated probe inserted approximately 2 cm and a Thermaalert TH-5 thermal monitor (Physitemp). Mice were singly housed in clean cages for 10 min, and three baseline body temperature measurements were taken. Ten minutes after the third baseline measurement, animals received 8-OH DPAT i.p. at the doses indicated and body temperature was monitored every 10 min for a total of 60 min. Temperatures are represented as a change from the final baseline measurement.

**Stress-Induced Hyperthermia**

Stress-induced hyperthermia paradigm measures a physiologic response to a stressful stimuli (Adriaen Bouwknegt et al., 2007). Briefly, animals in their home cages were moved to a testing room and allowed to acclimate for 1 hr. One animal per cage was removed and a baseline body temperature was measured intrarectally. Each animal was then placed in a novel, clean cage for 10 min, after which a second body temperature was recorded.

**Open Field Test**

Exploration in response to a novel open field was measured as described (Weisstaub et al., 2006), with the following modifications: (1) animals were singly housed for at least 30 min prior to testing to minimize order effects within a cage, (2) light levels in the open field chambers were maintained at 10–20 lux to encourage exploration of the full environment, (3) animals were placed in a corner of the maze and allowed to explore the center at will, and (4) the test was conducted for a total of 30 min. Dependent measures were the path length (cm), number of entries into the center, time in the center, and percent age of distance in the center (distance traveled in the center divided by the total distance traveled).

**Light/Dark Choice Test**

Exploration of the light/dark chamber was measured as described (Klemenhagen et al., 2006). Dependent measures were total distance and percentage of time spent in the light compartment.

**Modified Forced Swim Test**

Behavioral response to forced swimming was assayed as described previously (David et al., 2007). Briefly, mice were placed into clear plastic buckets 20 cm in diameter and 23 cm deep filled 2/3 of the way with 26°C water and videotaped from the side for 6 min. Only the last 4 min were scored. All animals were exposed to the swim test on two consecutive days. Scoring was done using an automated Viewpoint Videotrack software package. Dependent variables were immobility, swimming, and climbing.

**Tail Suspension Test**

Mice were suspended by the tail using tape to secure them to a horizontal bar. The animals were suspended for 5 min and immobility during this period was assessed using an automated Viewpoint Videotrack software package.

**Repeated Mild Stressor**

Animals were gavaged daily with 10 ml/kg/day of drinking water for 28 days prior to testing.

**Novelty Suppressed Feeding**

Testing was performed as previously described (David et al., 2007). Briefly, animals were food restricted for 24 hr and were place in a 40 x 60 cm brightly lit arena (800–900 lux) with a food pellet placed in the center. Latency of the animals to begin chewing food was recorded. Immediately after the latency was recorded, the food pellet was removed from the arena. The animals were then placed in their home cage and the amount of food consumed in 5 min was measured (home cage consumption), followed by an assessment of post-restriction weight. Percentage of body weight lost and home cage consumption were assessed as relative measures of animal hunger. No effect of fluoxetine was observed in home cage measures (Figure S3).

**Statistical Analysis**

In general, the effect of treatment or dose was analyzed using an ANOVA, using repeated measures where appropriate. Significant ANOVAs were followed up with Fisher PLSD test for behavioral and physiological measures and with Student-Neuman-Keuls t test for electrophysiological characterization. In the case of the NSF paradigm, survival analysis was performed and statistical differences were determined using the Kaplan-Meier product-limit method.

**SUPPLEMENTAL INFORMATION**

Supplemental Information includes one table and three figures and can be found with this article online at doi:10.1016/j.neuron.2009.12.003.

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