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Preclinical studies indicate that (2R,6R)-hydroxynorketamine (HNK) is a putative fast-acting antidepressant candidate. Although inhibition of NMDA-type glutamate receptors (NMDARs) is one mechanism proposed to underlie ketamine’s antidepressant and adverse effects, the potency of (2R,6R)-HNK to inhibit NMDARs has not been established. We used a multidisciplinary approach to determine the effects of (2R,6R)-HNK on NMDAR function. Antidepressant-relevant behavioral responses and (2R,6R)-HNK levels in the extracellular compartment of the hippocampus were measured following systemic (2R,6R)-HNK administration in mice. The effects of ketamine, (2R,6R)-HNK, and, in some cases, the (25,6S)-HNK stereoisomer were evaluated on the following: (i) NMDA-induced lethality in mice, (ii) NMDAR-mediated field excitatory postsynaptic potentials (fEPSPs) in the CA1 field of mouse hippocampal slices, (iii) NMDAR-mediated miniature excitatory postsynaptic currents (mEPSCs) and NMDA-evoked currents in CA1 pyramidal neurons of rat hippocampal slices, and (iv) recombinant NMDARs expressed in Xenopus oocytes. While a single i.p. injection of 10 mg/kg (2R,6R)-HNK exerted antidepressant-related behavioral and cellular responses in mice, the ED50 of (2R,6R)-HNK to prevent NMDA-induced lethality was found to be 228 mg/kg, compared with 6.4 mg/kg for ketamine. The 10 mg/kg (2R,6R)-HNK dose generated maximal hippocampal extracellular concentrations of ~8 μM, which were well below concentrations required to inhibit synaptic and extrasynaptic NMDARs in vitro. (25,6S)-HNK was more potent than (2R,6R)-HNK, but less potent than ketamine at inhibiting NMDARs. These data demonstrate the stereoselectivity of NMDAR inhibition by (2R,6R;25,6S)-HNK and support the conclusion that direct NMDAR inhibition does not contribute to antidepressant-relevant effects of (2R,6R)-HNK.

Significance

Standard antidepressant treatments require weeks to show effectiveness. A single subanesthetic dose of ketamine rapidly attenuates many clinical signs and symptoms of depression; however, ketamine treatment also has many adverse effects, including dissociation and potential for abuse, which are mediated by NMDA glutamate receptor (NMDAR) inhibition. Previous work has revealed that the ketamine metabolite (2R,6R)-hydroxynorketamine (HNK) induces antidepressant-like responses in rodents while minimizing the adverse effects observed with ketamine. The results of this study, using a multitude of experimental approaches, confirm that antidepressant-relevant concentrations of (2R,6R)-HNK are not sufficient to block NMDARs. This provides a basis for work directed at alternative molecular targets and toward novel drugs that exert rapid antidepressant effects independent of NMDAR inhibition and NMDAR-mediated adverse effects.

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Major depressive disorder (MDD) occurs in about 16% of the population over the course of a lifetime (1). It is estimated that MDD affected nearly 7% of all US adults in 2016, and that one-half of those individuals were prescribed typical antidepressant medications as part of their treatment regimen (2). Although such typical antidepressants, including selective serotonin and norepinephrine reuptake inhibitors, tricyclic antidepressants, and monoamine oxidase inhibitors, can sometimes mitigate clinical symptoms of MDD, the onset of action of these drugs is very slow, requiring daily administration over weeks or months for clinical improvement (3). In addition, ~30% of pa-
tients suffering from MDD fail to respond after attempting multiple treatments (3). The use of \((R, S)\)-ketamine (ketamine) for the treatment of MDD has generated much excitement because it reduces, and in some patients eliminates, many core symptoms of depression, including depressed mood, anhedonia, and suicidal ideation, within hours following i.v. administration of a single subanesthetic dose. Furthermore, ketamine is effective in patients who are refractory to typical antidepressants (4–9).

Although ketamine is a promising alternative to standard clinically used antidepressants, it induces adverse effects at antidepressant doses, particularly dissociation (10). Furthermore, ketamine, a derivative of the illicit drug phencyclidine, is widely abused (11). Ketamine is rapidly and stereoselectively metabolized in the liver to a number of metabolites, including the norketamines, hydroxketamines, dehydronorketamines, and the hydroxynorketamines (HNKs) (12). Demethylation of the methyl amine on ketamine’s central cyclohexyl ring generates the norketamines, which are then hydroxylated on the 4, 5, or 6 position of the cyclohexyl ring to form the HNKs. Following systemic ketamine administration, the 6-HNKs, that is \((2S, 6S:\text{2R}, 6R)-\text{HNK}\) (Fig. 1), are the major HNK metabolites found in human plasma and in rodent plasma and brain (13–15). Earlier studies in rodents found that ketamine and norketamine exert anesthetic effects, but \((2S, 6S:\text{2R}, 6R)-\text{HNK}\) does not (16). This finding contributed to the prevailing view that ketamine and possibly norketamine are the clinically active agents, whereas HNK metabolites are pharmacologically inactive (17–19). More recently, the \((2S, 6S:\text{2R}, 6R)-\text{HNK}\) metabolites, particularly the \((2R, 6R)-\text{HNK}\) stereoisomer, were found effective in inducing antidepressant-relevant behavioral and cellular responses in mice (14). \((2S, 6S)-\text{HNK}\) was also identified as a potential antidepressant, but with lower potency than \((2R, 6R)-\text{HNK}\) (14). Although the antidepressant-relevant effects of \((2R, 6R)-\text{HNK}\) were later confirmed by independent research groups using different model systems (20–28), the mechanism underlying these effects is unknown.

Despite the recognized inhibitory action of ketamine on N-methyl-d-aspartate receptors (NMDARs), \((2R, 6R)-\text{HNK}\) does not appear to inhibit NMDAR function in vitro or to induce adverse effects expected of an NMDAR antagonist in vivo (12, 14, 28–30). Instead, at concentrations associated with antidepressant-relevant effects, \((2R, 6R)-\text{HNK}\) has been found to produce robust synaptic potentiation of excitatory synaptic transmission in hippocampal slices (14). Nevertheless, reports that at high concentrations \((2R, 6R)-\text{HNK}\) inhibits NMDAR function led to the suggestion that NMDAR inhibition accounts for \((2R, 6R)-\text{HNK}\)’s antidepressant-relevant effects (31, 32).

The present study systematically assessed the effects of \((2R, 6R)-\text{HNK}\) on NMDAR function. Tests exploring behavioral despair and hyponeophagia in mice were employed to confirm the metabolite’s antidepressant-relevant effects. Analytical assays were used to quantify plasma, whole-brain, and extracellular hippocampal levels of \((2R, 6R)-\text{HNK}\) following systemic treatment of mice with a dose that produces antidepressant-relevant effects. A series of functional tests including in vivo NMDA-induced lethality and ex vivo electrophysiological measurements of NMDAR activity in hippocampal neurons and in oocytes expressing distinct NMDAR subtypes (GluN1/GluN2A, GluN2B, GluN2C, or GluN2D) were used to determine the potency for \((2R, 6R)-\text{HNK}\) to inhibit NMDARs. The results lead to the conclusion that \((2R, 6R)-\text{HNK}\) does inhibit NMDAR function, but only at concentrations substantially higher than those produced by doses resulting in antidepressant-relevant effects in mice.

**Results**

\((2R, 6R)-\text{HNK}, \text{at the Dose of 10 mg/kg, Exerts Antidepressant-Relevant Responses in Mice.}\) Mice received i.p. injections of either \((2R, 6R)-\text{HNK}\) (10 mg/kg) or vehicle \([0.9\% \ (\text{m/v}) \ \text{NaCl (saline), control}]) 1 or 24 h before being subjected to the forced swim test (FST), which assesses behavioral despair that is decreased by existing antidepressant drugs. Compared with saline-treated mice, mice treated with \((2R, 6R)-\text{HNK}\) showed significantly reduced immobility time at both time points (Fig. 2 A and B). This response is similar to that induced by ketamine and \((2R, 6R)-\text{HNK}\), as previously reported (14).

The novelty suppressed feeding (NSF) test assesses the time a food-deprived mouse waits until biting a food pellet located in the middle of an illuminated open-field arena. This hyponeophagic response time is decreased by antidepressant drugs (33). We employed this test 30 min after a single 10 mg/kg injection of \((2R, 6R)-\text{HNK}\) (i.p.) to understand whether antidepressant-like effects occur at an earlier time point than what has previously been reported (~1 h) (14). Mice that received \((2R, 6R)-\text{HNK}\) required a significantly shorter amount of time to bite a food pellet than did saline-treated mice (Fig. 2C). \((2R, 6R)-\text{HNK}\) administration did not change food consumption of the mice in their home cages, providing evidence that there were no appetite changes following drug administration that motivated approach times (consumption in g/10 min \([n = 10 \text{ mice/treatment}])\); control, 0.3 ± 0.04; \((2R, 6R)-\text{HNK}\), 0.4 ± 0.03; \(P = 0.3518\)).

Increased expression of mature BDNF (mBDNF) and activation of mTOR complex 1 (mTORC1) are considered important determinants of the effectiveness of antidepressants and can be detected 30 min after administration of ketamine (34, 35). Using immunoblots, we measured relative levels of mBDNF and its precursor, proBDNF, as well as levels of total and phosphorylated (activated) mTOR protein levels \([\text{mTOR and p-mTOR (Ser2448), respectively}]\) in hippocampal extracts obtained from mice 30 min after the i.p. injection of 10 mg/kg of \((2R, 6R)-\text{HNK}\) or saline. While \((2R, 6R)-\text{HNK}\) treatment had no significant effect on the expression of proBDNF or mTOR, it significantly increased mBDNF and p-mTOR levels in the hippocampus (Fig. 2D).

**Establishment of Antidepressant-Relevant Tissue Concentrations of \((2R, 6R)-\text{HNK} \text{ in Mice.}\) Following i.p. treatment of mice with the 10 mg/kg \((2R, 6R)-\text{HNK}\) dose shown to induce antidepressant-relevant effects (Fig. 2 A–D; also see ref. 14), the highest plasma concentration of \((2R, 6R)-\text{HNK}\) was 23.96 ± 0.66 μM at 2.5 min posttreatment. Plasma concentrations rapidly declined to 15.12 ± 0.72 μM at 5 min, 8.71 ± 0.60 μM at 10 min, and below quantification at 60 min postinjection (Fig. 2E). In the target organ (brain), the maximum concentration of \((2R, 6R)-\text{HNK}\) was 18.70 ± 0.47 μM/kg 5 min postinjection, with a decline to 10.15 ± 1.20 and 1.20 ± 0.17 μM/kg at 10 and 30 min postadministration, respectively, with levels below quantitation 1 h following injection (Fig. 2F).

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Fig. 1. Metabolism of \((R, S)\)-ketamine to the two hydroxynorketamine (HNK) stereoisomers, \((2R, 6R)-\text{HNK}\) and \((2S, 6S)-\text{HNK}\). The amine group at the chiral center (C2 carbon) of \((R)\)-ketamine and \((S)\)-ketamine undergoes demethylation, producing \((R)\)-norketamine and \((S)\)-norketamine, followed by hydroxylation at the C6 carbon cis to the amine group to give the \((2R, 6R)\)- and \((2S, 6S)-\text{HNKs}\). \((R)\)-Ketamine selectively forms \((2R, 6R)-\text{HNK}\), while \((S)\)-ketamine selectively forms \((2S, 6S)-\text{HNK}\). The primary intermediate metabolites, \((R)\)- and \((S)\)-norketamine, are not depicted.
Using microdialysis in freely moving mice, we measured $(2R,6R)$-HNK levels in the extracellular compartment of the hippocampus after an i.p. injection of 10 mg/kg $(2R,6R)$-HNK. Extracellular levels of $(2R,6R)$-HNK in the hippocampus reached a maximum $(7.57 \pm 2.13 \mu M)$ 10 min after the systemic administration (Fig. 2G). Clearance from the hippocampal extracellular space was slower than from plasma and whole-brain tissue. Approximately 30 min posttreatment, 39.1% of the measured highest concentrations remained in the hippocampal extracellular space $(2.96 \pm 0.79 \mu M)$, whereas only 15% and 12% of maximum $(2R,6R)$-HNK remained in the plasma and whole...
brain, respectively (Fig. 2 E and F). Extracellular concentrations of (2R,6R)-HNK in the hippocampus decreased to 0.37 ± 0.09 μM (3% of maximum) and 0.054 ± 0.015 μM (0.7% of maximum) by 1 and 4 h, respectively, after the systemic treatment of mice. We conclude that the concentrations in the extracellular compartment of the hippocampus treated systemically with the (2R,6R)-HNK dose of 10 mg/kg that induces antidepressant-relevant effects in mice are ≤10 μM.

Antidepressant-Relevant Doses of (2R,6R)-HNK Are Insufficient to Prevent NMDA-Induced Lethality. Prevention of lethality induced by systemic administration of NMDA is a historical measure of in vivo potency of drugs that inhibit NMDAR function (36–38). Here, mice were treated with a single i.p. injection of ketamine, (2R,6R)-HNK, or (2S,6S)-HNK, and 5 min later, injected with the LD50 of NMDA (250 mg/kg) (36). The doses of ketamine, (2R,6R)-HNK, and (2S,6S)-HNK that protected 50% of mice from NMDA-induced lethality (i.e., ED50) were 6.4, 227.8, and 18.6 mg/kg, respectively (Fig. 3A and Table 1). The calculated mean time to death at each of these ED50 values was ~30 min [28.3, 24.0, and 31.7 min for ketamine, (2S,6S)-HNK, (2R,6R)-HNK, respectively]. At doses that had no effect on NMDA-induced lethality, the mean time to death was <20 min.

The highest brain concentrations measured following treatment of a separate group of mice with the estimated ED50 values of ketamine (6.4 mg/kg, i.p.), (2R,6R)-HNK (227.8 mg/kg, i.p.), and (2S,6S)-HNK (18.6 mg/kg, i.p.) were 13.66 (5 min), 830.4 (5 min), and 30.8 (10 min) μM/kg, respectively (Fig. 3B). The area under the curve of brain concentrations vs. time between the first and last sampling time (AUClast) revealed that total brain levels over time were 3.05, 302.6, and 10.11 μM/kg h for ketamine, (2S,6S)-HNK, (2R,6R)-HNK, respectively. Thus, based on the brain concentrations produced by the ED50 values of the test compounds, ketamine is estimated to be 60- to 100-fold more potent than (2R,6R)-HNK in this in vivo measure of NMDAR function.

Antidepressant-Relevant Concentrations of (2R,6R)-HNK Are Insufficient to Inhibit Evoked NMDAR-Mediated Field Excitatory Postsynaptic Potentials in the Mouse Hippocampus. In nominally Mg2+-free ACSF at room temperature, ketamine, (2R,6R)-HNK, and (2S,6S)-HNK inhibited NMDAR-mediated field excitatory postsynaptic potentials (fEPSPs) in the CA1 field of mouse hippocampal slices, as evidenced by a concentration-dependent reduction of fEPSP slopes (Fig. 4).

While ketamine inhibited NMDAR-mediated fEPSPs with an IC50 of 4.5 μM, (2R,6R)-HNK inhibited these fEPSPs with a nearly 50-fold higher IC50 (211.9 μM; Fig. 4D and Table 1). The IC50 for (2S,6S)-HNK to inhibit fEPSPs was 47.2 μM (Fig. 4E and Table 1). Likewise, recordings obtained at 32–35 °C revealed that, at these physiologically relevant temperatures, 10 and 100 μM ketamine significantly reduced NMDAR-mediated fEPSP slopes by 76.3% ± 7.2 and 88.7% ± 6.1, respectively, whereas 10 and 100 μM (2R,6R)-HNK had no significant effect on these synaptic responses (SI Appendix, Fig. S1).

Antidepressant-Relevant Concentrations of (2R,6R)-HNK Are Insufficient to Inhibit NMDAR-Mediated Miniature Excitatory Postsynaptic Currents in Rat CA1 Pyramidal Neurons. NMDAR-mediated miniature excitatory postsynaptic currents (mEPSCs) were recorded from rat CA1 pyramidal neurons in the presence and absence of a range of concentrations of ketamine and (2R,6R)-HNK in nominally Mg2+-free ACSF (Fig. 5A). Ketamine and (2R,6R)-HNK reduced the mean amplitude of the mEPSCs in a concentration-dependent manner (Fig. 5B), with IC50 values of 6.4 and 63.7 μM, respectively (Table 1). The median event amplitudes measured from neurons following control superfusion were 10.57 ± 0.59 pA. Based on the 5-pa threshold for event detection, the largest possible reduction of event amplitude was ~52% of control existing, thereby the inhibition reached a plateau at ~60% of control.

The cumulative distributions of mEPSC amplitudes recorded in the presence of ≥10 μM ketamine and ≥50 μM (2R,6R)-HNK were also significantly shifted toward smaller amplitudes in comparison with control (Fig. 5C). Analysis of the frequency of events revealed that the reduction of mEPSC frequency by ketamine and (2R,6R)-HNK mirrored the reduction of the mEPSC amplitudes, suggesting that, in the presence of effective concentrations of the test compounds, many events became too small to be detected.

Antidepressant-Relevant Concentrations of (2R,6R)-HNK Are Insufficient to Inhibit NMDA-Induced Whole-Cell Current in Rat CA1 Pyramidal Neurons. Whole-cell currents induced by the admixture of NMDA (50 μM) and glycine (10 μM) delivered via a U-tube system were recorded from rat CA1 pyramidal neurons. Representative sample recordings obtained in the absence and in the presence of each test compound in Mg2+ (1 mM)-containing ACSF are shown in Fig. 6A. Ketamine reduced the total charge carried by NMDA-induced currents in a concentration-dependent manner (Fig. 6B). The IC50 for ketamine was estimated to be 45.9 μM (Fig. 6B and
Table 1). Likewise, (2S,6S)-HNK suppressed the NMDA-evoked currents (Fig. 6B); however, with only two test concentrations, the data could not be fitted for an IC_{50} calculation. In contrast, (2R,6R)-
HNK tested at concentrations ranging from 50 to 1,000 μM had no significant effect on NMDA-induced currents (Fig. 6).

**Antidepressant-Relevant Concentrations of (2R,6R)-HNK Are Insufficient to Inhibit NMDARs Regardless of Subunit Composition.** Rat GluN1/ GluN2A RNA was injected into Xenopus oocytes to form recombinant heterodimeric receptors of GluN1 and either GluN2A, GluN2B, GluN2C, or GluN2D. An admixture of glutamate/plus-glycine (100 μM each, 1000G/G) was applied to the oocytes to establish the maximum current amplitude. (2R,6R)-HNK or (2S,6S)-HNK was then applied to individual cells at ascending concentrations in combination with glutamate/glycine, and the difference in current was recorded as a percent inhibition from maximum. (2R,6R)-HNK and (2S,6S)-HNK concentration dependently reduced the amplitudes of glutamate/glycine-evoked currents in oocytes expressing different NMDAR subtypes. Based on the analysis of the concentration–response relationships, (2S,6S)-HNK inhibited the different NMDAR subtypes with markedly higher potency than did (2R,6R)-HNK (Fig. 7 and Table 1). The rank order of potency for the two compounds to block the distinct NMDAR subtypes also differed. For (2R,6R)-HNK, the rank order of potency was as follows: GluN1/GluN2C receptors (IC_{50}, 202 μM) > GluN1/GluN2A receptors (IC_{50}, 157 μM) > GluN1/GluN2D receptors (IC_{50}, 403 μM). In contrast, for (2S,6S)-HNK, the rank order of potency was as follows: GluN1/GluN2D (IC_{50}, ~13 μM) > GluN1/GluN2C (IC_{50}, 157 μM) > GluN1/GluN2B (IC_{50}, ~21 μM) > GluN1/GluN2A (IC_{50}, ~43 μM). Under similar conditions, the rank order of potency for ketamine was previously reported to be as follows: GluN1/2B (IC_{50}, 0.9 μM) > GluN1/2C (IC_{50}, 1.7 μM) > GluN1/2D (IC_{50}, 2.4 μM) > GluN1/2A (IC_{50}, 3.3 μM) (39).

The voltage dependence of the inhibitory effect of (2S,6S)-HNK on NMDA-induced lethality was also explored. (2S,6S)-HNK inhibition of each NMDAR subtype was voltage dependent (SI Appendix, Fig. S2). Specifically, less current passed through each receptor subtype in the presence of different concentrations (3–30 μM) of the metabolite relative to control when the cells were voltage clamped at progressively more negative holding voltages. The magnitude of the inhibitory effect of (2S,6S)-HNK on the four NMDAR subtypes decreased markedly as the membrane potentials became less negative, with the effect of all test concentrations in each NMDAR subtype becoming negligible at membrane potentials more positive than −10 mV.

**Discussion**

Ketamine has emerged as an alternative treatment for depression due to its fast onset of action and effectiveness in treating patients who are refractory to typical pharmacotherapies; however, the beneficial antidepressant effects of ketamine are accompanied by detrimental adverse effects, including dissociation and abuse potential, limiting its clinical utility (12). We and others reported that, in a number of preclinical models, the ketamine metabolite (2R,6R)-HNK induces antidepressant-relevant effects at similar doses as ketamine, without ketamine’s adverse effects at these doses (14, 20–28). It has been debated, however, whether NMDA inhibition, the mechanism proposed to underlie the antidepressant effects of ketamine, contributes to the antidepressant effects of (2R,6R)-HNK. The results of the present study reveal that the rank order of potency for inhibition of NMDAR function is ketamine > (2S,6S)-HNK > (2R,6R)-HNK regardless of animal species and type of NMDAR-mediated response measured in vivo or in vitro (mouse iEPSPs; rat mEPSCs and NMDA-evoked responses; glutamate-evoked responses in Xenopus oocytes expressing distinct rat NMDA subtypes; and NMDA-induced lethality). These findings support the hypothesis that direct inhibition of NMDARs by (2R,6R)-HNK is not a determinant of the antidepressant-relevant effects of this ketamine metabolite.

Systemic administration of 10 mg/kg (2R,6R)-HNK to adult male CD-1 mice suppressed behavioral despair and hyponeophagia in the FST (1 and 24 h following treatment) and the NSF test (30 min after treatment), respectively. This is in line with previous studies reporting antidepressant-relevant behavioral effects of (2R,6R)-HNK similar to those of ketamine in mice and rats (14, 20, 27, 28). We have previously reported antidepressant-relevant behavioral effects of (2R,6R)-HNK at doses ranging between 3 and 10 mg/kg (i.p.) in the FST (1, 24 h, and 3 d after administration), NSF (1 h after administration), reversal of learned helplessness behavior (24 h after administration), and chronic corticosterone-induced anhedonia, all in CD-1 mice. Additionally, reversal of social defeat-induced social interaction deficits was observed in C57BL/6J mice 24 h after i.p. administration of 20 mg/kg (2R,6R)-HNK (14). BALB/cJ mice treated with (2R,6R)-HNK, delivered via an i.p. injection (10 mg/kg) or directly to the medial prefrontal cortex, also exhibited 24 h later antidepressant-related behaviors in the FST consistent with those induced by similar treatments with ketamine (20). (2R,6R)-HNK, administered i.p. (10 or 30 mg/kg) or directly to the medial prefrontal cortex, resulted in sustained antidepressant-like effects on a number of outcomes assessed in C57BL/6J mice (27). In addition, Chou et al. (24) reported that rats exhibited antidepressant-relevant behaviors 1 h and up to 21 d after a single i.p. administration of (2R,6R)-HNK (10 mg/kg). We note one research group has reported being unable to detect antidepressant-relevant behavioral effects of (2R,6R)-HNK in rodent behavioral tests (41, 42). Hence, it remains to be determined whether (2R,6R)-HNK is sufficient to elicit antidepressant-relevant behaviors in vivo at concentrations less than those required to prevent NMDA-induced lethality. (2R,6R)-HNK doses greater than 200 mg/kg were required to prevent the lethal effect of NMDA (Fig. 3A). In contrast, NMDA-induced lethality was prevented in ~60%–70% of the tested mice pretreated with previously reported antidepressant doses of ketamine (10 mg/kg, i.p.) or (2S,6S)-HNK (25 mg/kg, i.p.) (14). Thus, while an antidepressant-relevant dose of (2R,6R)-HNK is well below doses needed to inhibit NMDARs in vivo, antidepressant doses of ketamine and (2S,6S)-HNK overlap those required to inhibit an NMDA-mediated response in vivo. The ED_{50}s required to prevent NMDA-induced lethality resulted in peak brain concentrations of ~14, 830, and 31 μmol/kg for ketamine, (2R,6R)-HNK, and (2S,6S)-HNK, respectively, indicating that remarkably high in vivo concentrations of (2R,6R)-HNK are necessary for NMDAR inhibition. These data strongly argue that NMDAR inhibition in vivo is not a predicted characteristic underlying the antidepressant-relevant actions of ketamine and (2R,6R)-HNK.

In the nominal absence of extracellular Mg^{2+}, ketamine, (2R,6R)-HNK, and (2S,6S)-HNK reduced the slope of NMDAR-mediated iEPSPs in the CA1 field of mouse hippocampal slices, with the rank order of potency being ketamine > (2S,6S)-HNK > (2R,6R)-HNK (Table 1). Under similar experimental conditions, ketamine was found to be approximately 10-fold more potent than (2R,6R)-HNK in reducing the amplitude of the mEPSCs recorded from CA1 pyramidal neurons in rat hippocampal slices. Neither mEPSCs nor fEPSPs were significantly blocked by 10 μM (2R,6R)-HNK; a concentration comparable to the hippocampal extracellular C_{max} generated by an antidepressant-relevant dose of this metabolite (Fig. 2G). In contrast, at concentrations of ketamine that result in antidepressant-like efficacy (i.e., 10 μM; ref. 14), mEPSC amplitudes and fEPSP slopes were suppressed by >50%.

In the presence of 1 mM extracellular Mg^{2+}, NMDA-plus-glycine-evoked whole-cell currents in CA1 pyramidal neurons of the rat hippocampus were insensitive to (2R,6R)-HNK concentrations as high as 1 mM. These NMDAR-mediated whole-cell currents were blocked by the test compounds with the same order of potency as that observed for NMDAR-mediated synaptic responses in the nominal absence of Mg^{2+}, that is, ketamine > (2S,6S)-HNK > (2R,6R)-HNK. It is noteworthy, however, that the IC_{50} for ketamine to block whole-cell currents evoked by NMDA-plus-glycine was found to be ~50 μM, which is markedly greater than the IC_{50} for
Fig. 4. Concentration–response relationship for (R,S)-ketamine, (2R,6R)-HNK, and (2S,6S)-HNK to inhibit NMDAR fEPSPs in the CA1 field of mouse hippocampal slices. NMDAR-mediated fEPSPs were recorded before and after superfusion of slices with various concentrations of ketamine (KET), (2R,6R)-HNK, and (2S,6S)-HNK. (A–C) Sample recordings of fEPSPs obtained before and during exposure to the slices to KET, (2R,6R)-HNK, or (2S,6S)-HNK are shown. Traces in blue represent baseline potentials. Traces in red, green, and orange represent fEPSPs recorded in the presence of ketamine, (2R,6R)-HNK, or (2S,6S)-HNK, respectively. Traces in gray represent fEPSPs recorded after application of APV. Graphs of changes in fEPSP slope as a function of concentrations of (D) KET and (2R,6R)-HNK and (E) (2S,6S)-HNK. The respective vehicle control values are plotted in blue. Data points and error bars represent mean and SEM, respectively [n = 4–7 slices/test compound concentration; (R,S)-KET and (2R,6R)-HNK control, n = 36; (2S,6S)-HNK control, n = 19 (controls for each concentration were run separately for blinding purposes)]. The IC50 values of ketamine, (2R,6R)-HNK, and (2S,6S)-HNK were found to be 4.5, 211.9, and 47.2 μM, respectively (Table 1).
Concentration 26: controls for each con-
response relationship for (Lumsden et al.
8 neurons/test compound concentration; control, 
values were estimated to be 6.4
www.pnas.org/cgi/doi/10.1073/pnas.1816071116 = 
( ) oocytes demonstrated that among the experiments. As ketamine is a noncompetitive 
10 ms concentrations, as previously mentioned.
Xenopus 20, and oo-
Xenopus > evoked whole-cell currents in
(2
affects the
(open-channel blocker at NMDARs (12), extracellular Mg
NMDARs, GluN1/GluN2A receptors were the least sensitive to
inhibition by ketamine, (2,6S)-HNK, (2,6R)-HNK, and (2R,6R)-HNK of <5, 10–20, and >100 μM respectively, to displace [3H]MK-801 binding to the PCP/ketamine binding site of the NMDAR in rat forebrain homogenates (12, 14, 29, 30, 44, 45). However, there are discrepancies among the IC50 values estimated on the basis of re-
duction of fEPSP slopes, mEPSC amplitudes, and amplitudes of glutamate-plus-glycine-evoked whole-cell currents in Xenopus oo-
cytes expressing distinct NMDAR subtypes (Table 1). These differ-
cences may be explained by the different preparations used, distinct
acellular location and receptor subtypes assessed, and the use of varying extracellular Mg
substitutions, (GluN1/GluN2B, GluN1/GluN2C, and GluN1/GluN2D), respectively.
Each electrophysiological experiment in this study supported an
NMDAR inhibition rank order of ketamine > (2S,6S)-HNK >
(2R,6R)-HNK, a conclusion in agreement with the published in-
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24 h after i.p. administration of 10 mg/kg (2R,6R)-HNK or ketamine to mice (20). In vitro, similar to ketamine, 10 μM (2R,6R)-HNK was reported to translocate G_{α} from lipid raft domains to nonraft domains and increase intracellular cAMP (21), up-regulate AMPA receptor (AMPAR) subunit mRNA expression in cell culture at a concentration of 0.4 μM (25), and enhance structural plasticity in mouse mesencephalic and human induced pluripotent stem cell-derived dopaminergic neurons via AMPAR-driven BDNF and mTOR signaling at a concentration of 0.5 μM (23). According to results obtained in the present study, mBDNF and phosphorylated mTOR levels in hippocampal extracts were also significantly increased 30 min after administration of 10 mg/kg (2R,6R)-HNK to mice. The earlier report that (2R,6R)-HNK treatment lacked effect on mTOR phosphorylation or mature BDNF levels at a later time point (i.e., 1 h postinjection) in mice (14) can be reconciled by the fact that, in that study, mTOR phosphorylation and BDNF expression were assessed in synaptosome fractions instead of total extracts. In addition, the possibility cannot be ruled out that immediate changes in mBDNF and mTOR activation occur in a narrow time window following a treatment (34, 35) and may, therefore, have been missed in the earlier study. Indeed, Fukumoto et al. (27) recently reported increases in mTOR phosphorylation at 30 min, but not 60 min, postinjection in the medial prefrontal cortex and also found that (2R,6R)-HNK antidepressant-relevant responses are mTORC1 and BDNF activity dependent.

Ex vivo studies revealed that antidepressant-relevant concentrations of (2R,6R)-HNK produce a robust potentiation of AMPAR-mediated excitatory synaptic transmission in slices from the hippocampus (14) and the midbrain ventrolateral periaqueductal gray of rats (24). By 24 h after administration of 10 mg/kg (2R,6R)-HNK or ketamine to mice, induction of long-term potentiation was impaired in the nucleus accumbens and AMPAR-mediated responses were depressed in ventral tegmental area dopaminergic neurons (22). The
finding that administration of an AMPAR antagonist to mice blocked the antidepressant behavioral effects of (2R,6R)-HNK suggests that modulation of AMPAR activity plays a role in the antidepressant-relevant effects of (2R,6R)-HNK (14).

Although there are a multitude of treatment options for depression, typical pharmacotherapies require daily administration over multiple weeks before improvement is expected, with many patients failing to find an effective therapy (3). The discovery that a single administration of ketamine rapidly relieves depressive symptoms has brought upon hopes for new therapies; however, ketamine’s many adverse effects and abuse potential due to NMDAR inhibition pose serious challenges for its clinical use. Overall, we found that at antidepressant-relevant concentrations/doses, (2R,6R)-HNK is unable to inhibit NMDARs, potentially accounting for its reduced adverse behavioral effects compared with ketamine. The NMDAR-independent antidepressant actions of the ketamine’s metabolite (2R,6R)-HNK and of other compounds that may share (2R,6R)-HNK’s antidepressant-relevant mechanisms, may provide safe, fast-acting, and effective alternatives to the currently approved pharmacological treatments for MDD.

Table 1. ED$_{50}$ and IC$_{50}$ for NMDAR inhibition by ketamine, (2R,6R)-HNK, and (2S,6S)-HNK

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Ketamine</th>
<th>(2R,6R)-HNK</th>
<th>(2S,6S)-HNK</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED$_{50}$ mg/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMDA-induced lethality</td>
<td>6.4</td>
<td>227.8</td>
<td>18.6</td>
</tr>
<tr>
<td>IC$_{50}$ μM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMDAR-mediated fEPSP slope</td>
<td>4.5</td>
<td>211.9</td>
<td>47.2</td>
</tr>
<tr>
<td>NMDAR-mediated mEPSC amplitude</td>
<td>6.4</td>
<td>63.7</td>
<td>N/A</td>
</tr>
<tr>
<td>NMDA-induced whole-current charge</td>
<td>45.9</td>
<td>&gt;1,000</td>
<td>&gt;1,000</td>
</tr>
<tr>
<td>GluN1A/2A-mediated current amplitude</td>
<td>3.3*</td>
<td>498</td>
<td>43</td>
</tr>
<tr>
<td>GluN1A/2B-mediated current amplitude</td>
<td>0.9*</td>
<td>258</td>
<td>21</td>
</tr>
<tr>
<td>GluN1A/2C-mediated current amplitude</td>
<td>1.7*</td>
<td>202</td>
<td>15</td>
</tr>
<tr>
<td>GluN1A/2D-mediated current amplitude</td>
<td>2.4*</td>
<td>287</td>
<td>13</td>
</tr>
</tbody>
</table>

*Refers to previously published data obtained under similar conditions (39).
minutes after each treatment, mice received an i.p. injection of 250 mg/kg NMDA, and the number of mice that survived 24 h was recorded.

Hippocampal Slice and Xenopus laevis Oocyte Electrophysiology. See detailed methods described in SI Appendix, SI Materials and Methods.

Experimental Design Statistical Analysis. All in vitro and in vivo tests and data analyses were performed by experimenters who were blind to treatment assignments. To analyze the effects of (2R,6R)-HNK in the FST, unpaired Student’s t-tests were used for each time point. For assessment of the NMDA results, Kaplan-Meier survival analysis was used followed by the Mantel–Cox log-rank test. Probit analysis was used to determine the ED50 of each test compound to prevent NMDA-induced lethality in mice (i.e., the dose required to reduce lethality by 50%). Latencies for lethality against drug doses were plotted as second-order polynomial (quadratic) curves. The polynomial equation Y = B0 + B1X + B2X2 (quadratic equation; where Y is latency for lethality, and X is dose of the drug) was used to determine the time needed for the animals to die following the NMDA injection at the ED50. Unless otherwise noted, IC50 values were estimated from four-parameter Hill fits using GraphPad Prism, version 7.04 (GraphPad Software). All data are available per request.

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