Original Investigation

Positron Emission Tomography Quantification of Serotonin_{1A} Receptor Binding in Suicide Attempters With Major Depressive Disorder

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**IMPORTANCE** Serotonergic system dysfunction has been associated with increased lethal suicide attempts and suicide. Dysfunction includes higher binding of serotonin_{1A} autoreceptor in the brainstem raphe of individuals who die by suicide.

**OBJECTIVES** To determine the relationships between brain serotonin_{1A} binding and suicidal behavior in vivo in major depressive disorder (MDD) using positron emission tomography and the serotonin_{1A} antagonist radiotracer carbon C-11-{-labelled WAY-100635.

**DESIGN, SETTING, AND PARTICIPANTS** Cross-sectional positron emission tomography study at an academic medical center from 1999 through 2009. We compared serotonin_{1A} binding between individuals with MDD who did not attempt suicide (nonattempters) (n = 62) and those who attempted suicide (attempters) (n = 29). We subdivided the attempters into those with lower (n = 16) and higher (n = 13) levels of lethality.

**MAIN OUTCOMES AND MEASURES** The binding potential (BP_{F}) of \(^{11}C\)WAY-100635 (calculated as the number of receptors available divided by affinity) in the prefrontal cortex (PFC) and brainstem, estimated by kinetic modeling with an arterial input function; the severity of suicidal behaviors, including lethality and intent of suicide attempts; and suicidal ideation.

**RESULTS** Using a linear mixed-effects model, we found no difference between attempters and nonattempters with MDD in serotonin_{1A} BP_{F} in the PFC regions (\(F_{1,88} = 0.03; P = .87\)) or in the raphe nuclei (\(F_{1,88} = 0.29; P = .59\)). Raphe nuclei serotonin_{1A} BP_{F} was 45.1% greater in higher-lethality attempters compared with lower-lethality attempters (\(F_{1,25} = 7.33; P = .01\)), whereas no difference was observed in the PFC regions (\(F_{1,25} = 0.12; P = .73\)). Serotonin_{1A} BP_{F} in the raphe nuclei of suicide attempters was positively correlated with the lethality rating (\(F_{1,25} = 10.56; P = .003\)) and the subjective lethal intent factor (\(F_{1,25} = 10.63; P = .003; R^2 = 0.32\)) based on the most recent suicide attempt. Suicide ideation in participants with MDD was positively correlated with serotonin_{1A} BP_{F} in the PFC regions (\(F_{1,88} = 5.19; P = .03\)) and in the raphe nuclei (\(F_{1,87} = 7.38; P = .008; R^2 = 0.12\)).

**CONCLUSIONS AND RELEVANCE** Higher brainstem raphe serotonin_{1A} BP_{F} observed in higher-lethality suicide attempters with MDD is in agreement with findings in suicide studies and also with the finding of low cerebrospinal fluid levels of 5-hydroxyindoleacetic acid in higher-lethality suicide attempters. Higher brainstem raphe serotonin_{1A} BP_{F} would be consistent with lower levels of serotonin neuron firing and release and supports a model of impaired serotonin signaling in suicide and higher-lethality suicidal behavior. Severity of suicidal ideation in MDD is related to brainstem and prefrontal serotonin_{1A} BP_{F}, suggesting a role for both regions in suicidal ideation. Lower levels of serotonin release at key brain projection sites, such as the prefrontal regions, may favor more severe suicidal ideation and higher-lethality suicide attempts.

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Suicide claimed the lives of more than 38,000 individuals in the United States in 2010. Although the majority of suicides occur in the setting of a current psychiatric disorder, most commonly major depressive disorder (MDD), most individuals with MDD never attempt suicide. Of those who do, fewer make higher-lethality attempts, confounding efforts to detect and mitigate suicide risk. Thus, an urgent need exists for in vivo biomarkers of suicide risk to assist clinical identification and management of such high-risk patients.

Biological studies of suicidal behaviors occurring within major depressive episodes repeatedly have identified evidence of central serotonin system hypofunction. Low cerebrospinal fluid (CSF) levels of 5-hydroxyindoleacetic acid (5-HIAA), serotonin’s primary metabolite within the central nervous system, have been associated with prior suicide attempts, particularly violent and/or highly lethal attempts, and the prospective risk for suicide. Serotonin release in response to the serotonergic agent fenfluramine hydrochloride also appears to be impaired in individuals with higher-lethality suicide attempts (attempters), as indicated by a blunted prolactin response. In higher-lethality suicide attempters, the suicidal intent is greater and the CSF levels of 5-HIAA are lower; a lifetime history of more severe aggression is also correlated with lower CSF levels of 5-HIAA. However, CSF measures and neuroendocrine challenge studies do not provide information about the anatomical location of brain abnormalities within the serotonergic system or offer an explanation of the mechanism responsible for lower-level functioning of the serotonin system.

Uptake of fludeoxyglucose F 18 (FDG) in positron emission tomography (PET) is lower in the ventral, medial, and lateral prefrontal cortex (PFC) in higher-lethality suicide attempters who are depressed compared with lower-lethality attempters who are depressed; these differences become more pronounced on challenge with fenfluramine and are related to higher levels of suicidal intent and lower levels of impulsiveness. Suicidal intent is also related to lower uptake of carbon 11 ([C]labeled methyltryptophan in the ventromedial PFC, whereas aggression is related to lower ventromedial FDG uptake in the PFC and lower serotonin transporter binding in the anterior cingulate. These findings provide some possible regional specificity to serotonergic abnormalities related to suicidality.

Postmortem studies of individuals who die by suicide (completers) find differences in serotonergic system markers in the brainstem and PFC regions. Findings include higher binding of serotonin1A autoreceptor in the dorsal raphe nucleus in suicides, particularly in the rostral dorsal raphe nucleus, and higher levels of serotonin1A autoreceptor binding in the ventrolateral PFC, although not all studies find the PFC difference.

Cerebrospinal fluid 5-HIAA and PET FDG uptake studies in higher-lethality suicide attempters and serotonin1A binding in suicide completers post mortem suggest a common biological substrate between suicide and higher-lethality nonfatal suicide attempts in MDD. In contrast, serotonergic function in lower-lethality suicide attempters appears more similar to that of individuals who do not attempt suicide (hereinafter referred to as nonattempters). Therefore, we assessed the relationship between serotonin1A binding in vivo and a history of suicide attempts in a large cohort with current MDD using PET imaging and the serotonin1A antagonist radiotracer [11C]WAY-100635. We hypothesized that we would find higher levels of binding in the PFC and midbrain raphe nuclei in higher-lethality suicide attempters with MDD compared with lower-lethality attempters with MDD. We also explored correlations between serotonin1A autoreceptor binding and the severity of suicidal ideation and depression psychopathology.

### Methods

#### Participants

The institutional review board of the New York State Psychiatric Institute approved the protocol. All participants provided written informed consent for study procedures.

We included 91 individuals who met *DSM-IV* criteria for a current major depressive episode and a diagnosis of MDD in this secondary analysis of data from a sample largely overlapping but expanded from previous reports. This sample included 29 suicide attempters (consisting of 16 lower-lethality and 13 higher-lethality suicide attempters defined by a median split based on the lethality rating of the most recent suicide attempt). Inclusion criteria were assessed through psychiatric interview, medical record review, the Structured Clinical Interview for *DSM-IV*, Patient Edition, physician-obtained medical history, review of systems, results of a physical examination, and results of laboratory tests. These tests included a complete blood cell count, chemistry panel, thyroid function tests, urinalysis, and urine screening for drugs; female participants also underwent pregnancy testing. The diagnosis of MDD based on the Structured Clinical Interview for *DSM-IV* was conducted by experienced research masters- and doctoral-level psychologists. A team of experienced clinical research psychologists and psychiatrists (G.M.S., M.A.O., and A.B.) reviewed all diagnoses. The k scores for the MDD diagnosis were greater than 0.85. The Beck Depression Inventory, Hamilton Depression Rating Scale (the 17-item scale for screening and the 24-item scale for severity correlations with binding), and Global Assessment Scale assessed subjective and objective depression severity and functional impairment, respectively. Diagnoses of Axis II personality disorder were determined using the Structured Clinical Interview for *DSM-IV* Axis II Personality Disorders. The behavioral data reported on suicide attempts refer to the most recent attempt for participants reporting more than one attempt. All suicide attempt data were gathered using the Columbia Suicide History Form, which uses clinical probes and anchor points to identify suicide attempts chronologically that meet the Columbia Classification Algorithm of Suicide Assessment criteria and documents the method and medical damage of each suicide attempt. The Medical Lethality Scale scores medical damage caused by a suicide attempt on a scale ranging from 0 (no injury) to 8 (fatal), with anchor points dependent on the method of the attempt. The assessment also incorporates the Beck Scale for Suicide Ideation for all participants and the...
PET Quantification of Serotonin$_{1A}$ Receptor Binding

**History of Medication Use**

A previous study$^{46}$ has shown that antidepressant-naive individuals with current MDD have higher $[^{11}C]$WAY-100635 binding potential (BP$_F$) values in the brain, indicating higher serotonin$_{1A}$ binding compared with healthy volunteers. In a comprehensive replication of this effect of MDD on serotonin$_{1A}$ binding,$^{25}$ patients with MDD were categorized as not recently receiving medication (NRM) and recently receiving medication (RM), with NRM defined as no history of antidepressant exposure within the 4 years before the study. The NRM group included patients with MDD and no lifetime antidepressant exposure and patients with MDD who were not treated with antidepressants for at least the previous 4 years because those 2 groups did not differ in their composite binding data.

We used this classification in the present analyses, which include a larger sample of NRM (n = 49) and RM (n = 42) participants with MDD than in the previous studies.$^{25,26}$ Those participants who could not recall the name or dose of a medication or the duration of therapy and for whom records of medication history were otherwise unavailable were classified as indeterminate (n = 13) and were not included. Because lower levels of binding were observed in the RM group,$^{26}$ this potential medication effect was controlled for in all analyses.

The sample of NRM participants with MDD in the present study has 19 additional participants added to the previously described sample of 30 participants concerning the effect of MDD on serotonin$_{1A}$ binding.$^{25}$ Sixty-three additional participants with MDD were added to the 28 participants with MDD in the previous report of an effect of MDD on serotonin$_{1A}$ binding.$^{26}$

**Derivation of Regional Outcome Measures**

The outcome measure of choice in PET neuroreceptor studies is the total number of receptors available (B$_{avail}$) in vivo to bind the radioligand divided by the receptor ligand affinity (K$_D$). However, without multiple injections and occupancy of the receptors, current technology permits only measurement of BP$_F$ = B$_{avail}$/K$_D$. Fortunately, no evidence exists for alterations in serotonin$_{1A}$ K$_D$ in depression.$^{25}$ Regional distribution volumes (V) of $[^{11}C]$WAY-100635 are derived from kinetic analysis using the arterial input function and a 2-tissue compart-
A 1-tissue compartment model was used. For the CWM, a 1-tissue compartment model was used. The contribution of plasma total activity to the regional activity was calculated as:

\[ \text{BPF} = \frac{V_T(\text{ROI}) - V_T(\text{CWM})}{V_T(\text{CWM})} \]

Prelativetothenoiseinmeasuringitjustifiesadjusting

With Attempters

Statistical Analysis

To borrow strength across ROIs and to account for correlation among ROIs properly in the same participant, we fit linear mixed-effects models to the ROI-level BPF estimates, with region and group as fixed effects and participant as the random effect, providing a powerful test of our primary hypothesis with the need to correct for multiple comparisons. To stabilize variance across regions, adjust for slight skewness in distribution of binding measures, and allow a proportional change in binding across regions, we fit the model to log-transformed binding potentials. Log transformation has been used in multiple previous PET studies to address these issues. Other groups have used related statistical approaches, including linearizing transformation and nonparametric testing, to address these issues in analyzing PET data. Demonstrating a difference in log binding potential is equivalent to demonstrating a difference in the same direction of raw BP. Because the natural log is a monotone transformation, we computed estimated SEs using a bootstrap algorithm that takes into account errors in metabolite, plasma, and brain data with observations weighted accordingly. Analyses were performed using commercially available software (SPSS Statistics, version 20.0 [IBM Corp, 2011] or R software). All tests were 2 tailed.

### Results

SerotoninBPf in Nonattempters Compared With Attempters

Clinical and demographic characteristics of the nonattempters and attempters with MDD are summarized in Table 1. The

Table 1. Demographic and Clinical Characteristics of the Attempter and Nonattempter MDD Groupsa

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Study Group</th>
<th>Group Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suicide Nonattempters</td>
<td>Suicide Attempters</td>
</tr>
<tr>
<td></td>
<td>(n = 62)</td>
<td>(n = 29)</td>
</tr>
<tr>
<td>Age, y</td>
<td>40.4 (12.4)</td>
<td>34.6 (12.3)</td>
</tr>
<tr>
<td>Educational level, y</td>
<td>14.9 (3.2)</td>
<td>14.1 (4.3)</td>
</tr>
<tr>
<td>HDRS-24 score</td>
<td>25.7 (6.7)</td>
<td>27.6 (6.1)</td>
</tr>
<tr>
<td>Beck Depression Inventory score</td>
<td>26.8 (9.6)</td>
<td>30.7 (10.4)</td>
</tr>
<tr>
<td>Beck SSI score</td>
<td>3.4 (5.5)</td>
<td>9.7 (11.6)</td>
</tr>
<tr>
<td>Beck Suicide Intent Scale score</td>
<td>NA</td>
<td>14.4 (5.0)</td>
</tr>
<tr>
<td>Lethality of attempt score</td>
<td>NA</td>
<td>1.6 (1.7)</td>
</tr>
<tr>
<td>Lifetime score</td>
<td>18.2 (4.9)</td>
<td>19.2 (5.1)</td>
</tr>
<tr>
<td>Global Assessment Scale score</td>
<td>54.0 (10.6)</td>
<td>48.0 (10.9)</td>
</tr>
<tr>
<td>Reasons for Living Scale score</td>
<td>2.2 (2.4)</td>
<td>1.6 (1.9)</td>
</tr>
<tr>
<td>Beck Hopelessness Scale score</td>
<td>9.9 (6.7)</td>
<td>13.3 (5.3)</td>
</tr>
<tr>
<td>Age at onset of MDE, y</td>
<td>23.5 (12.1)</td>
<td>17.9 (10.3)</td>
</tr>
<tr>
<td>Female sex, %</td>
<td>64.5</td>
<td>65.5</td>
</tr>
<tr>
<td>Cluster B personality disorder, %</td>
<td>12.2</td>
<td>32.0</td>
</tr>
<tr>
<td>Lifetime history of abuse, %</td>
<td>56.7</td>
<td>60.7</td>
</tr>
<tr>
<td>History of abuse before 15 years of age, %</td>
<td>45.0</td>
<td>46.4</td>
</tr>
<tr>
<td>SSI score &gt;0 at baseline, %</td>
<td>37.1</td>
<td>48.3</td>
</tr>
<tr>
<td>Specific activity, mCi/nmol</td>
<td>3.85 (1.80)</td>
<td>3.55 (1.85)</td>
</tr>
<tr>
<td>Injected dose, mCi/kg</td>
<td>0.09 (0.05)</td>
<td>0.10 (0.04)</td>
</tr>
<tr>
<td>Injected mass, mg/kg</td>
<td>0.02 (0.01)</td>
<td>0.03 (0.02)</td>
</tr>
<tr>
<td>MDE, major depressive episode</td>
<td>NA</td>
<td>1.6 (1.7)</td>
</tr>
<tr>
<td>Suicide Ideation</td>
<td>NA</td>
<td>14.4 (5.0)</td>
</tr>
<tr>
<td>HDRS-24 score</td>
<td>25.7 (6.7)</td>
<td>27.6 (6.1)</td>
</tr>
<tr>
<td>MDE, major depressive episode</td>
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</tr>
<tr>
<td>MDE, major depressive episode</td>
<td>NA</td>
<td>1.6 (1.7)</td>
</tr>
</tbody>
</table>

Abbreviations: BPf, plasma-free fraction; HDRS-24, 24-item version of Hamilton Depression Rating Scale; MDD, major depressive disorder; MDE, major depressive episode; NA, not applicable; SSI, Scale for Suicide Ideation; VT(CWM), volume of distribution in cerebellar white matter.

f by 3.7 × 10^3.  

f Unless otherwise indicated, data are expressed as mean (SD).

f Determined using the Brown-Goodwin Lifetime History of Aggression Scale for SI nonattempters and 26 attempters.

f Indicates some ideation is present at entry into the study.

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1. The distribution volumes of the nondisplaceable (VND) and specific (VS) compartments were defined. The total regional equilibrium distribution volume (VT) was equal to the sum of VND and VS. Time activity curves were fit with a 2-tissue compartment model, with the K1:K2 ratio fixed to that of the CWM (the reference region with virtually no serotonin receptors). For the CWM, a 1-tissue compartment model was used. We calculated the BPf as (VT(ROI) − VT(CWM))/fP. The contribution of plasma total activity to the regional activity was calculated assuming a 5% blood volume in the ROI and subtracted from the total activity before statistical analyses. Kinetic parameters were derived by nonlinear regression using software programmed in MATLAB. The BPf measures maximum specific binding divided by K0, and involves the fewest assumptions about tracer delivery, clearance, and protein binding. Although some uncertainty remained in measuring fP, we expected that the extent of the participant-to-participant variability in fP relative to the noise in measuring it justifies adjusting for it on the participant level. Partial volume effects should be comparable for higher- and lower-lethality suicide attempters. To some degree, the effect of fP and any other index on measurement error is mitigated by the weightings that we used.

2. Statistical Analysis

To borrow strength across ROIs and to account for correlation among ROIs properly in the same participant, we fit linear mixed-effects models to the ROI-level BPf estimates, with region and group as fixed effects and participant as the random effect, providing a powerful test of our primary hypothesis without the need to correct for multiple comparisons. To stabilize variance across regions, adjust for slight skewness in distribution of binding measures, and allow a proportional change in binding across regions, we fit the model to log-transformed binding potentials. Log transformation has been used in multiple previous PET studies to address these issues. Other groups have used related statistical approaches, including linearizing transformation and nonparametric testing, to address these issues in analyzing PET data. Demonstrating a difference in log BPf is equivalent to demonstrating a difference in the same direction of raw BPf because the natural log is a monotone transformation. We computed estimated SEs using a bootstrap algorithm that takes into account errors in metabolite, plasma, and brain data with observations weighted accordingly. Analyses were performed using the nlme package in the R software environment (http://www.r-project.org). Additional statistical analyses, including the t test, χ2 test, and Fisher exact test, were performed using commercially available software (SPSS Statistics, version 20.0 [IBM Corp, 2011] or R software). All tests were 2 tailed.

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3. Results

SerotoninBPf in Nonattempters Compared With Attempters

Clinical and demographic characteristics of the nonattempters and attempters with MDD are summarized in Table 1. The
PET Quantification of Serotonin<sub>1A</sub> Receptor Binding

Serotonin<sub>1A</sub> BPF in Lower- vs Higher-Lethality Attempters

Clinical and demographic characteristics of the lower- and higher-lethality attempters with MDD are summarized in Table 2. In addition to a higher mean lethality score of the most recent suicide attempt, the higher-lethality group also had greater suicidal intent. Otherwise, both attempter subgroups were comparable on demographic and clinical variables and the radiotracer administration parameters <i>f</i><sub>a</sub> and <i>V</i><sub>TCWMD</sub>.

The higher-lethality attempters with MDD had higher serotonin<sub>1A</sub> BPF in the raphe nuclei compared with the lower-lethality attempters with MDD (%1 = 7.33; <i>P</i> = .01). Binding of the serotonin<sub>1A</sub> autoreceptor was 45.4% higher in the higher-lethality attempters. In all attempters with MDD, the lethality rating and serotonin<sub>1A</sub> BPF binding in the raphe nuclei were positively correlated (%1 = 10.56; <i>P</i> = .003; R<sup>2</sup> = 0.32) (Figure 1). In contrast in the PFC, serotonin<sub>1A</sub> BPF did not differ between the higher- and lower-lethality attempter groups (%1 vs %X; %1 = 0.12; <i>P</i> = .73). We found no relationship between lethality and the PFC serotonin<sub>1A</sub> BPF (%1 = 1.70; <i>P</i> = .20). No effects of sex (%1 = 0.04; <i>P</i> = .85) or prior antidepressant status (%1 = 1.04; <i>P</i> = .32) on raphe nuclei binding were observed.

When the presence of a cluster B personality disorder diagnosis was considered as a predictor in the model, the effect of lethality on the raphe nuclei serotonin<sub>1A</sub> BPF remained significant (%1 = 7.84; <i>P</i> = .01), and no effect of cluster B personality disorder diagnosis on binding was found (%1 = 0.01; % = .93). The degree of intent to attempt suicide or the degree of planning correlates with the lethality of the attempt (29 participants; R<sup>2</sup> = 0.617; <i>P</i> < .001). This finding may reflect the lower lethality observed in more impulsive, less planned at-
Serotonin1A BP and Suicide Intent Rating in Attempters

Total Beck Suicide Intent Scale score and the raphe nuclei serotonin1A BP were positively correlated ($F_{1,25} = 7.89; P < .01$), which post hoc analyses showed was accounted for by factor 1 (subjective lethal intent) ($F_{1,25} = 10.63; P = .003; R^2 = 0.32$) (Figure 2) and not factor 2 (objective planning) ($F_{1,25} = 2.05; P = .16$). No relationship was found between the PFC region serotonin1A BP and the Beck Suicide Intent Scale score ($F_{1,25} = 0.09; P = .76$) or with either factor score.

Relationships Among Serotonin1A BP, Suicide Ideation, and Depression Severity

In the entire MDD group, the Beck Scale for Suicide Ideation score was positively correlated with serotonin1A BP in PFC regions ($F_{1,88} = 5.19; P = .03$), with a significant effect of prior antidepressant status ($F_{1,88} = 7.28; P < .01$). The Beck Scale for Suicide Ideation score was also related to serotonin1A BP in the raphe nuclei ($F_{1,87} = 7.38; P = .008; R^2 = 0.12$) (Figure 3), but raphe nuclei binding was not significantly related to prior antidepressant status ($F_{1,87} = 3.86; P = .053$). Depression severity, as rated on the 24-item version of the Hamilton Depression Rating Scale, was not related to raphe nuclei ($F_{1,87} = 1.65; P = .20$) or to PFC ($F_{1,88} = 0.18; P = .67$) binding.

Discussion

Consistent with postmortem studies showing higher dorsal raphe nuclei serotonin1A binding in individuals who die by committing suicide and with our hypothesis, we found that higher-lethality suicide attempters with MDD have higher...
raphe nuclei serotonin$_{1A}$ BP$_F$ compared with lower-lethality attempters with MDD. In contrast, serotonin$_{1A}$ BP$_F$ did not differ when all attempters with MDD were compared with all nonattempters with MDD. Within both suicide attempter groups with MDD (higher and lower lethality), lethality of the most recent suicide attempt was positively correlated with raphe nuclei binding; the Beck Suicide Intent Scale score was also positively correlated with binding. The degree of suicide intent correlated moderately with the lethality of suicide attempts, as has been reported. Thus, higher serotonin$_{1A}$ binding in vivo in higher-lethality attempters and in postmortem examination of individuals who complete suicide may represent a common biological marker of risk for higher lethality and intent or more serious suicidal behavior. Such a biological commonality between suicide and more lethal suicide attempts is also apparent in the demographic similarities (more men and older individuals) and in the clinical picture of more depression and less impulsiveness. Less lethal suicide attempts are more characteristic of women and younger individuals and are more impulsive.

Somatodendritic serotonin$_{1A}$ autoreceptors in the raphe nuclei inhibit raphe serotonergic neuron firing and thus the frequency of serotonin release from terminals. Therefore, higher raphe nuclei serotonin$_{1A}$ binding in higher-lethality attempters with MDD may indicate less neuronal firing and less serotonin release at terminal projection regions in the forebrain favoring higher-lethality suicide attempts. We also find greater suicide intent correlated with higher raphe nuclei serotonin$_{1A}$ binding, and suicide intent correlates with more lethal suicidal behavior.

Our finding of higher serotonin$_{1A}$ binding in higher-lethality suicide attempters with MDD is consistent with low CSF 5-HIAA levels in higher-lethality attempters with MDD and future suicide completers with MDD and is consistent with a blunted prolactin response to a fenfluramine-stimulated serotonergic challenge in higher-lethality suicide attempters. These results further indicate that higher raphe nuclei serotonin$_{1A}$ binding may be a marker of more serious suicidal behavior in those at risk for suicide attempts.

Serotonin$_{1A}$ binding is 17% to 30% higher in PFC regions post mortem in individuals who complete suicide compared with those with nonsuicide deaths assayed using the serotonin$_{1A}$ agonist 8-OH-DPAT. Agonists bind to the subset of receptors in the agonist high-affinity state. The antagonist radiotracer $[^{11}C]$WAY-100635 binds to agonist high- and low-affinity states of serotonin$_{1A}$. Nonhuman primate PET imaging comparing a serotonin$_{1A}$ agonist tracer and $[^{11}C]$WAY-100635 indicates that only about half of the total binding of $[^{11}C]$WAY-100635 in the PFC regions is attributable to high-agonist affinity receptors. In serotonin$_{1A}$ BP$_F$ in the raphe nuclei, we detected more than 45.1% higher binding in higher-lethality attempters, a difference that is comparable to that reported in individuals who complete suicide. Our median split for dividing attempters into higher- and lower-lethality groups was a score between 1 and 2, whereas prior CSF studies had a cut point between 2 and 3. We had fewer higher-lethality attempters in our study, which limited our power to detect binding differences associated with greater lethality.

Among all 91 participants with MDD, suicidal ideation in the 2 weeks before PET imaging was positively correlated, albeit weakly ($R^2 = 0.12$), with serotonin$_{1A}$ BP$_F$ in the raphe nuclei and PFC regions. This finding suggests a more general role for serotonin$_{1A}$ signaling in determining suicidal ideation severity, and severity of suicidal ideation can predict risk for future suicide.

Cluster B personality disorders are typically associated with more impulsive behaviors. The lower-lethality attempter group had about 3 times the rate of cluster B personality disorders (46.2%) compared with the higher-lethality attempter group (16.7%). This difference suggests that the higher raphe nuclei serotonin$_{1A}$ binding in higher-lethality attempters represents a biomarker for suicide attempts that are associated with more intent and with less impulsive traits or fewer personality disorders. Consistent with this model, we find better planned, less impulsive suicide attempts are more lethal. Objective and subjective depression severity and hopelessness were comparable between the higher- and lower-lethality attempter groups, and, as previously reported, serotonin$_{1A}$ binding was not related to depression severity.

In terms of the causes of higher serotonin$_{1A}$ binding that we observed in higher-lethality attempters with MDD, there are a few possibilities. The first is the C(-1019)G genetic variant in the promoter of the serotonin$_{1A}$ gene (HTR1A [HGNC 5286]), where the G allele is associated with greater expression in the brainstem serotonin neurons, and higher raphe nuclei autoreceptor binding is seen on PET imaging. Second, animal studies of developmental adversity report that maternal deprivation in rodent models can upregulate binding in some brain regions, such as the hippocampus, although not the raphe nuclei autoreceptors. In the nonhuman primate, peer rearing is associated with in vivo serotonin$_{1A}$ binding differences by PET that are sex dependent. We did not detect an effect on binding of reported childhood (younger than 15 years) adversity. In fact, we found no effect of abuse at any age. Considering abuse in our model did not alter the significance of the lethality effect on binding. Therefore, we found no evidence that adversity explained the higher raphe nuclei binding or that it contributed to the effect of lethality.

Diminished serotonin activity could be caused by other factors, such as lower tryptophan hydroxylase 2 activity or expression. However, postmortem studies in depressed individuals who complete suicide have found greater tryptophan hydroxylase 2 expression and more serotonin neurons within raphe nuclei; therefore, other mechanisms, such as serotonin$_{1A}$ autoreceptor overexpression, must be responsible for the hyposerotonergic state we observed in our sample of higher-lethality attempters.
This study has some limitations. Although this study has, to our knowledge, the largest sample size for a published PET study of this receptor, the numbers in the MDD attempter subgroups were too small to determine whether higher binding was associated with the G allele or reported childhood adversity. We detected lower serotonin_1A binding in participants reporting use of antidepressants within 4 years of PET scanning, in agreement with a previous report. All analyses therefore controlled for this factor. Recruiting a sample of antidepressant-naive participants is challenging logistically and is not representative of most clinical populations. The mean age of the attempters with MDD was about 6 years younger than that of the nonattempters with MDD, but previous studies have not identified an effect of age on the binding of [11C]WAY100635 in the age range of this study.

ARTICLE INFORMATION
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Author Contributions: Dr Sullivan had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Sullivan, Oquendo, Parsey, Mann.
Acquisition, analysis, or interpretation of data: Sullivan, Oquendo, Milak, Miller, Burke, Ogden, Mann. Drafting of the manuscript: Sullivan, Oquendo, Parsey.
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PET Quantification of Serotonin 1A Receptor Binding


