In Vivo Imaging of Histone Deacetylases (HDACs) in the Central Nervous System and Major Peripheral Organs

Changning Wang,† Frederick A. Schroeder,‡† Hsiao-Ying Wey,† Ronald Borra,† Florence F. Wagner,§ Surya Reis,‡ Sung Won Kim,∥ Edward B. Holson,§ Stephen J. Haggarty,‡ and Jacob M. Hooker*†

†Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, 73 High Street, Charlestown, Massachusetts 02129, United States
‡Chemical Neurobiology Laboratory, Departments of Neurology and Psychiatry, Center for Human Genetic Research, Massachusetts General Hospital, 185 Cambridge Street, Boston, Massachusetts 02114, United States
§Stanley Center for Psychiatric Research, Broad Institute of Harvard and MIT, 7 Cambridge Center, Cambridge, Massachusetts 02142, United States
∥Laboratory of Neuroimaging, National Institute on Alcohol Abuse and Alcoholism, Bethesda, Maryland 20892, United States

Supporting Information

Abstract: Epigenetic enzymes are now targeted to treat the underlying gene expression dysregulation that contribute to disease pathogenesis. Histone deacetylases (HDACs) have shown broad potential in treatments against cancer and emerging data supports their targeting in the context of cardiovascular disease and central nervous system dysfunction. Development of a molecular agent for non-invasive imaging to elucidate the distribution and functional roles of HDACs in humans will accelerate medical research and drug discovery in this domain. Herein, we describe the synthesis and validation of an HDAC imaging agent, [11C]6. Our imaging results demonstrate that this probe has high specificity, good selectivity, and appropriate kinetics and distribution for imaging HDACs in the brain, heart, kidney, pancreas, and spleen. Our findings support the translational potential for [11C]6 for human epigenetic imaging.

Introduction

Eukaryotic cellular identity, growth, and homeostasis, extending to the level of organs, systems, and whole organisms depends in part on refined and adaptive regulatory control of gene expression. Investigation of epigenetic mechanisms—non-genetic determinants of gene expression variability—has highlighted the role of chromatin modifying enzymes in integrating environmental cues into biological effects via changes in transcriptional activity.

To date, much attention in this regard has been paid to the histone deacetylase (HDAC) family of enzymes.1−16 HDAC enzymes are divided into four different classes based on sequence homology, cellular localization, and phylogenetic relationships to yeast homologues: class I (HDACs 1, 2, 3, and 8), class IIa (HDACs 4, 5, 7, and 9), class IIb (HDACs 6, 10), class III (Sirtuins 1−7), and class IV (HDAC 11). Abnormal expression levels (both increased and decreased expression) of HDAC 1, 2, 3, and 6 that have been correlated with many diseases, including several forms of cancer, heart failure, inflammatory diseases, and cognitive and psychiatric disorders (Table 1). However, our knowledge of normal HDAC density and alterations in HDACs with human disease remains extremely limited and invasive methodologies used so far to investigate HDAC distribution17,18 are not compatible with translational medicine. Therefore, our goal was to develop a positron emission tomography (PET) imaging probe, which can quantify the density of HDAC 1, 2, 3, and 6 in vivo. Evaluating the expression and distribution of epigenetic machinery in vivo will improve our understanding of their relationship with disease and would provide an opportunity to intervene with treatment.

The challenge for HDAC research is developing a technique for quantifying the HDAC density that can be used in living subjects. The non-invasive imaging technique, PET, is an excellent tool to visualize chromatin-modifying enzymes in animals and human. PET can provide molecular level insight into protein density and interaction with drugs by quantifying the distribution of a radiotracer with extraordinarily high sensitivity. To date there are no validated tools for assessing the densities of HDAC enzymes in human despite the importance of these enzymes and their remarkably high expression. Efforts by others have resolved non-invasive probes for imaging HDAC enzyme density in vivo,19−23 however these tools have...
rapid binding kinetics and poor brain penetrating ability or bind to a different subset of HDACs than the isofoms that have been extensively implicated in diseases via study of patients and preclinical animal models.

Herein, we report the development of \(^{11}C\)(E)-3-(4-(((3r,5r,7r)-Adamantan-1-ylmethyl)(methyl)amino)methyl)-N-hydroxyacrylamide (\(^{11}C\)Martinostat, \(^{11}C\)6) (Figure 1) as a molecule ready for translation to human PET imaging (HDAC 1, 2, 3, and 6). Compound 6 is an adamantane-based hydroxamic acid with selective binding to HDAC 1, 2, 3, and 6 with subnanomolar potency and fast binding kinetics. Using rodent and nonhuman primate PET imaging, we demonstrate robust uptake and high specific binding in brain, heart, spleen, kidney, and pancreas. Using this tool, measurement of HDAC density of target isoforms 1, 2, 3, and 6 is possible in peripheral organs and brain for the probe with broad disease applicability, we wanted to integrate a structural subunit that confers CNS distribution in several drugs classes including antiviral drugs, cannabinoid receptor modulators. Further, adamantane-based hydroxamic acids were recently reported and showed strong evidence of HDAC inhibition.\(^{27}\) Using these previous studies to guide our synthesis efforts, we designed compound 6, a cinnamic acid-based HDAC inhibitor containing an adamantyl group as a ‘blood brain barrier (BBB) carrier’ (Figure 1). Compound 6 was synthesized through reductive amination, followed by conversion into a hydroxamic acid in the presence of hydroxylamine and sodium hydride. The radiosynthesis of \(^{11}C\)6 was accomplished using its desmethyl precursor in DMSO with \(^{11}C\)methyl iodide (\(^{11}C\)CH\(_3\)) as outlined in Scheme 1.

### Physicalchemical Properties of 6 and ex Vivo Binding.

The in vitro inhibitory activities of 6 were measured for each HDAC isoform HDAC1 through HDAC9 (Table 2) using recombinant human enzymes, with IC\(_{50}\) values for the FDA

<table>
<thead>
<tr>
<th>disease/process</th>
<th>selected evidence of HDAC 1, 2, 3, and 6 involvement</th>
<th>refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>neurodegenerative disorders</td>
<td>HDAC 1 and 3 protein complex integrity linked to neuronal cell death</td>
<td>1, 2</td>
</tr>
<tr>
<td></td>
<td>HDAC 1 expression is elevated in vulnerable brain regions of mouse and human models</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>HDAC 2 is elevated in Alzheimer’s patient and brain</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>HDAC 6 overexpression in patients with AD</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>HDAC 1 overexpression in the prefrontal cortex disrupts working memory</td>
<td>6</td>
</tr>
<tr>
<td>learning and memory</td>
<td>HDAC 2 loss improves working memory and accelerates extinction learning</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>HDAC 1 and 2 are critical mediators of autophagy and cardiac plasticity</td>
<td>8</td>
</tr>
<tr>
<td>heart failure</td>
<td>Class I HDAC enzymes alter cardiomyocyte hypertrophy via ERK kinase activity</td>
<td>9</td>
</tr>
<tr>
<td>asthma</td>
<td>HDAC 2 deficiency in cells blunts transcriptional response to steroids and anti-inflammatory drugs.</td>
<td>10</td>
</tr>
<tr>
<td>cancer (general)</td>
<td>HDAC acetylation of p53 mediates tumor cell survival</td>
<td>11</td>
</tr>
<tr>
<td>breast cancer</td>
<td>HDAC 6 mRNA expression may have potential both as a marker of endocrine responsiveness and as a prognostic indicator in breast cancer</td>
<td>12</td>
</tr>
<tr>
<td>colon cancer</td>
<td>HDAC 3 turnover is induced in cells by isothiocyanate therapeutics</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>HDAC 1 and NuRD complex contributes to epigenetic silencing of colorectal tumor suppressor genes</td>
<td>14</td>
</tr>
<tr>
<td>ovarian cancer</td>
<td>HDAC 1 and 3 overexpression confer cisplatin resistance in ovarian cancer cell lines</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>HDAC 1 and 3 overexpression mediate proliferation and migration of ovarian cancer cells</td>
<td>16</td>
</tr>
</tbody>
</table>

Figure 1. \(^{11}C\)6: a translational PET imaging probe. We have developed a potent HDAC imaging agent, termed \(^{11}C\)6, incorporating three key structural features to create a versatile and translational probe for visualizing HDAC expression in vivo. Intravenous injection of trace amounts of \(^{11}C\)6 (nanogram scale) in baboon and imaging by PET-MR demonstrates quantifiable uptake in the brain and in diverse peripheral organs. This illustrates the potential for \(^{11}C\)6 as a broadly applicable tool in evaluating HDAC density in humans.

### RESULTS Design and Synthesis of PET Imaging Agents with Brain Permeability.

HDAC inhibitors comprise diverse structural classes including hydroxamic acids, natural cyclic peptides, and short-chain fatty acids as well as aminoanilines and ketones. Most classes of HDAC inhibitors contain three main structural elements to their pharmacophore: (i) a capping group, (ii) a linker domain, and (iii) a zinc-binding group, critical for enzyme action. Modification of these structural elements has so far revealed that the brain uptake of most HDAC inhibitors is limited.\(^{19,24}\) To develop an HDAC PET probe with broad disease applicability, we wanted to integrate a chemical structure that would exhibit robust exposure to both peripheral organs and the brain. In medicinal chemistry efforts by others, the adamantyl group has been identified as a structural subunit that confers CNS distribution in several drugs classes including antiviral drugs,\(^{25}\) cannabinoid receptor modulators.\(^{26}\) Further, adamantane-based hydroxamic acids were recently reported and showed strong evidence of HDAC inhibition.\(^{27}\) Using these previous studies to guide our synthesis efforts, we designed compound 6, a cinnamic acid-based HDAC inhibitor containing an adamantyl group as a ‘blood brain barrier (BBB) carrier’ (Figure 1). Compound 6 was synthesized through reductive amination, followed by conversion into a hydroxamic acid in the presence of hydroxylamine and sodium hydride. The radiosynthesis of \(^{11}C\)6 was accomplished using its desmethyl precursor in DMSO with \(^{11}C\)methyl iodide (\(^{11}C\)CH\(_3\)) as outlined in Scheme 1.
**Scheme 1. Synthesis of 6, Its Radiolabeling Precursor (4) and $[^{11}C]6^a$**

![Scheme 1](image)

"Reagents and conditions: (a) NaBH₄, MeOH, overnight, rt, 75%; (b) formaldehyde, AcOH, NaBH₃, MeOH, rt, overnight, 55%. (c) NH₂OH (aq), 1M NaOH, MeOH/THF, 0 °C to rt, 4 h, 42% for 6, 40% for 5; RCY of $[^{11}C]6$, 3–5% (non-decay corrected to trapped $[^{11}C]CH₃I$).

---

**Table 2. HDAC Selectivity, Potency, and Efficacy of 6 Compared To SAHA$^a$**

<table>
<thead>
<tr>
<th>assay</th>
<th>6</th>
<th>SAHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC₅₀ (nM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDAC 1</td>
<td>0.3</td>
<td>4.0</td>
</tr>
<tr>
<td>HDAC 2</td>
<td>2.0</td>
<td>11</td>
</tr>
<tr>
<td>HDAC 3</td>
<td>0.6</td>
<td>3.0</td>
</tr>
<tr>
<td>HDAC 4</td>
<td>1970</td>
<td>&gt;30000</td>
</tr>
<tr>
<td>HDAC 5</td>
<td>352</td>
<td>8750</td>
</tr>
<tr>
<td>HDAC 6</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>HDAC 7</td>
<td>&gt;20000</td>
<td>&gt;30000</td>
</tr>
<tr>
<td>HDAC 8</td>
<td>&gt;15000</td>
<td>1020</td>
</tr>
<tr>
<td>HDAC 9</td>
<td>&gt;15000</td>
<td>&gt;30000</td>
</tr>
<tr>
<td>EC₅₀ (nM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3K9ac</td>
<td>100</td>
<td>3400</td>
</tr>
<tr>
<td>H4K12ac</td>
<td>100</td>
<td>1900</td>
</tr>
</tbody>
</table>

"In vitro IC₅₀ (nM) values using recombinant human enzymes for HDAC subtypes 1–9 and specific substrates demonstrate that 6 is a selective inhibitor of HDAC 1–3 (0.3–2.0 nM) with decreased potency to inhibit HDAC 6 (4.1 nM) or other subtypes (>352 nM).

Compared to SAHA, the hydroxamate HDAC inhibitor SAHA exhibited lower affinity for HDAC targets 1–3 (3.0–11 nM). Dose–response plots in cultured primary mouse neuronal cells measuring relative H3K9ac and H4K12ac levels revealed potent induction of histone acetylation (EC₅₀) by 6 (100 nM) compared to SAHA (1900–3400 nM).

![Table 2](image)

---

approved HDAC inhibitor drug, suberoylanilide hydroxamic acid, vorinostat (SAHA), measured in parallel as a reference (to assess the variability among different assays). Compound 6 showed nanomolar IC₅₀ values for class-I HDAC isoforms (HDAC 1–3, 0.3, 2.0, and 0.6 nM, respectively), and the class-IIB HDAC 6 (4.1 nM), with >100-fold selectivity over each of the other HDAC isoforms assayed. Using $[^{11}C]6$ in vitro, we measured the partition coefficient (log D) at 2.03 and calculated tP50 of 52.5, which are in the preferred range for brain penetration, and further detected plasma protein binding (PPB), as measured in blood from baboon (1.4% unbound) and human (5.5% unbound), at levels consistent with those for the clinical dopamine D₂ receptor radiotracer, $[^{11}C]$raclopride$^{28}$ (Figure S1).

---

To test the selective binding of 6 over other potential protein targets, we screened the percentage inhibition of 6 (50 nM) using radioligand displacement assay against 4 zinc-dependent enzymes including matrix metalloproteinases and 80 additional non-HDAC or Zn-dependent central nervous system (CNS) targets. We determined minimal if any off-target binding, indicating high selectivity of 6 to the HDAC family (Table S1). The only potential off-target binding was the dopamine transporter (DAT) as implicated by the in vitro test. 6 (50 nM) resulted in a 24% inhibition of DAT (where 50% inhibition is the minimum threshold to identify a potential binding event). Therefore, to exclude a putative binding interaction of 6 to DAT (given that it is a relatively high dentistry brain protein), we used the established radiotracer $[^{11}C]β$-CFT to evaluate DAT density/occupancy in rats and observed no impact of 6 treatment (1 mg/kg, ip, 90 min prior) (Figure S2).

To further establish that $[^{11}C]6$ binding was specific for HDAC targets, we conducted blocking studies via autoradiography on rat brain sections ex vivo. We observed that specific binding of $[^{11}C]6$ was reduced by preincubation of sagittal rat brain sections with either of the unlabeled HDAC inhibitors: SAHA, a hydroxamic acid-based HDAC inhibitor (selective for class I and IIB HDAC isoforms), or CI-994, a benzamide-based HDAC inhibitor (selective for HDAC 1, 2, and 3 isoforms) (Figure S1C,D).

**In Vivo PET-CT Imaging with $[^{11}C]6$ in Rodents. High Brain Uptake and Reversible Binding.** To first test $[^{11}C]6$ as a radiotracer in vivo, we conducted PET imaging focused on rat brain. Using PET-CT, we determined that $[^{11}C]6$ exhibited high BBB penetration and sustained binding over the scanning time (60 min) when administered by intravenous bolus injection (0.9–1.1 mCi per animal), as shown in Figure S3A. To confirm that $[^{11}C]6$ was not effluxed from the brain by the xenobiotic pump, P-glycoprotein (P-gp), we measured radioligand uptake in brain after treatment with the P-gp inhibitor, cyclosporin A (CsA), and found no difference compared to control treatment (Figure S4A). Additionally, $[^{11}C]6$ binding in the rat brain was disrupted by an iv challenge with unlabeled 6 20 min after tracer administration as evidenced by a rapid decrease in the time–activity curve slope. This rapid loss of
radioactivity from brain regions provided confirmation of the reversibility of $[^{11}\text{C}]6$ binding to CNS targets (Figure S4B).

To determine the stability of $[^{11}\text{C}]6$ in brain, we measured the presence of radiolabeled parent compound and polar...
metabolites in homogenized rat brain tissue 30 min post-in vivo injection of $[^{11}C]6$. By eluting extracted and homogenized rat brain with solvents containing fractional increases of acetonitrile in water, we resolved a pattern of radioactivity indicating intact parent compound in the brain with limited degradation over the duration of a typical 30–90 min PET scan (Figure SSA). A similar pattern indicating unmetabolized $[^{11}C]6$ was observed in baboon plasma, 5 min post-injection of the tracer (Figure SSB).

**Dose-Dependent Blockade.** To investigate the specificity of $[^{11}C]6$, we performed PET imaging studies in rats with a 5 min pretreatment of unlabeled $6$ at different doses (0.001, 0.1, 0.5, and 2.0 mg/kg). We found that $[^{11}C]6$ binding in brain was blocked in a dose-dependent manner with a stepwise reduction in the percent tracer uptake after administration of unlabeled $6$ (Figure S3B). To test the sensitivity of $[^{11}C]6$ against other HDAC inhibitors, we pretreated a rat with CNS54, a highly brain penetrant hydroxamic acid HDAC inhibitor as determined by LC-MS-MS (brain/plasma = 4.5 after 20 min administration of CNS54 at 10 μg/kg iv), and SAHA, a hydroxamic acid HDAC inhibitor with limited brain penetrating ability.24 As expected, there was robust in vivo blockade of radioactivity in brain with the treatment of CNS54, but not SAHA (Figure S3C).

**In Vivo PET-MR Imaging with $[^{11}C]6$ in Baboon.** High Uptake in the Brain and Dose-Dependent Blockade. Next, we chose to utilize nonhuman primates to evaluate the distribution and specificity of $[^{11}C]6$. In baboons, we found that high brain uptake (50–60 in $V_T$, total volume of distribution) of $[^{11}C]6$ based on PET-MR focused on the head. Similar to the blocking results we obtained in rats, injection of unlabeled $6$ (0.5 and 1.0 mg/kg, iv) dose-dependently reduced the radioactivity uptake (measured as $V_T$) in specific brain regions including cerebellum, cortex, putamen, and caudate (Figure 2). The averaged $B_{max}$ of whole brain, 19.6 ± 2.9 μM of protein, was calculated from the PET image on the basis of the established relationship between total binding and dissociation rate29 and was consistent with ex vivo protein quantification in rodents by two methods.30 Physiological effects (i.e., respiration rate, blood pressure, heart rate, and end-tidal CO$_2$) were unchanged at any administered dose of $6$ or $[^{11}C]6$. The baboons used in these imaging studies were not sacrificed.

**Arterial Plasma Analysis.** After $[^{11}C]6$ intravenous bolus injection, radioactivity in arterial plasma clears rapidly as expected and as depicted in Figure S5C. Polar metabolites were observed in the plasma (50% of the plasma radioactivity after 10 min); however, radioactivity in brain tissue of rodents at late time points (30 min post administration) was associated almost exclusively with the parent molecule. These data support that the PET images for the brain tissue largely represent $[^{11}C]6$ and not radiolabeled metabolites. For quantitative analysis of the NHP PET imaging data, a metabolite-corrected arterial input function was used.

**Kinetic Modeling Shows High Specific Binding.** Two-tissue compartmental modeling was applied to analyze dynamic $[^{11}C]6$ PET data, corrected for arterial input function and parent compound metabolism to interpret results from intact and perfused radiotracer. Based on the modeling results (Figure 2), blocking with 0.5 and 1.0 mg/kg, $V_T$ decreased in all brain regions. Based on our rodent experiments and dose-equilibration for body mass, we assumed that a 1.0 mg/kg dose would provide full saturation of HDAC binding. Therefore, 50–80% of the signal represented specific binding in the selected brain regions suggesting that $[^{11}C]6$ has sufficient sensitivity to assess a wide range of CNS diseases in which HDAC may be altered, such as Alzheimer’s disease and in mood disorders,33,34,35 and for evaluation of drug-HDAC engagement.

**High uptake and blockade in peripheral organs.** We further evaluated the tracer uptake and blockade in peripheral organs in baboons. $[^{11}C]6$ showed high uptake in major organs including heart, kidney, pancreas, and spleen (Figure 3). The uptake in these organs was markedly decreased by pretreatment with unlabeled $6$, indicating that the $[^{11}C]6$ signal also represents HDAC expression in peripheral organs. To further confirm the sensitivity of $[^{11}C]6$ to detect changes in HDAC occupancy, we measured radiotracer uptake in the baboon both before and after 75 min infusion of SAHA (5 mg/kg, iv). We found that radiotracer uptake in peripheral tissue was robustly blocked by SAHA infusion, consistent with efficient distribution of this HDAC inhibitor blocking agent in nonbrain organs24 (Figure S6).

### DISCUSSION

Epigenetic therapies that target regulatory mechanisms of the human genome represent an emerging class of novel therapeutic agents. The importance of understanding aberrant enzyme expression of chromatin modifying enzymes including HDACs is highlighted by the discovery that protein coding mutations may play a role in human disease pathologies linked to cancer in major organs, cardiac dysfunction, and CNS disorders. The impact of these enzyme density changes is further implicated in disease as recent large-scale genome-wide association studies (GWAS) have shown that gene regulatory regions key in many common human diseases harbor an enrichment of single nucleotide polymorphisms (SNPs).33–38 This evidence of deregulated gene expression mechanism points to a more general need to target epigenetic machinery that may be causally involved in disease pathogenesis. Therefore, developing therapeutics for many human diseases can be best accomplished by first understanding the density and distribution of epigenetic machinery including HDAC enzymes in vivo.

Development of specific PET radiotracers to measure HDAC density or any other epigenetic component, with high uptake and major organs, is challenging.39 There are a number of major factors (summarized here A through D) that determine the success of a radiotracer candidate. Some factors can be predicted from in vitro assays (e.g., binding affinity and selectivity), and those which are more empirically determined (e.g., specific to nonspecific binding ratio). (A) The binding affinity and selectivity of a radiotracer for its target must be high enough to produce sufficient signal to background for detection and selective for the target so that images represent the biological target. (B) Additionally, radiotracers must exhibit specific binding, which is challenging to predict but can be easily measured by presaturating the target with an unlabeled (nonradioactive) form of the radiotracer thus resulting in decreased binding of radiotracer to its target. Unlabeled compound binding is also expected to alter the distribution and pharmacokinetics of the radioligand. (C) For CNS imaging, small molecules must cross the BBB. In general, small molecular weight (<400 Da) molecules with relatively high lipophilicity are required for a tracer to sufficiently penetrate the BBB. Predictive models based on PET imaging...
data are emerging for HDAC inhibitors that suggest the total polar surface area (tPSA) needs to be <65 Å² (D) With all of the above properties satisfied, a tracer candidate can still be renderable unusable in vivo if it is metabolized rapidly and those metabolites pervade the tissue regions of interest. Each of the primary factors for a successful radiotracer is met by [11C]6 and supported by our biochemical and preclinical imaging data. Of the more than 100 compounds we assessed through our tracer identification work, [11C]6 was unique. While we have observed some trends in molecular properties, structure, and in vivo behavior, fully understanding the molecular basis for [11C]6 success will require additional structure–activity relationship determination and computational modeling.

Our data support [11C]6 as a new tool to visualize HDAC density in the body and brain. The robust and blockable brain uptake with [11C]6 as a PET probe can be used to quantify HDAC density in brain disorders, such as neurodegenerative diseases and mood disorders, and for demonstrating target engagement of putative HDAC inhibitor therapeutics early in compound development pipeline. We found stable probe uptake in diverse peripheral organs in nonhuman primates, each with a distinct profile of HDAC target density and affinity as evidenced by time–activity curve (TAC) shape (Figure S6). In each case, we further demonstrated that [11C]6 binding could be prevented using a known, clinically applied HDAC inhibitor drug (Figure S6) illustrating the direct utility of this probe for understanding systemic impact of a cancer therapeutic. A recent report demonstrates that class I HDAC inhibition by a prototypical HDACi therapeutic, MS-275, stimulates renal dysfunction. Dose-limiting toxicity may not be surprising given the widespread expression and central role of HDACs in normal biological function. However, this underscores a mechanism-based liability for HDAC inhibitor leads proposed to date as CNS disease therapeutics where large mass dosing strategies are used to reach effective concentrations of HDACi in brain.

Importantly, the ability to simultaneously measure HDAC target engagement in peripheral organs and brain is a major development in not only understanding CNS disease mechanisms but also in prioritizing novel HDAC inhibitors with minimal systemic burden.

In summary, [11C]6 binds to HDAC subtypes (HDAC 1, 2, 3, and 6) with high selectivity and specificity and provides a tool for quantitative imaging of HDAC density in the brain and in peripheral organs in vivo. [11C]6 can be used as a PET radioligand for studying HDACs in disorders where altered regulation of HDACs is found. The approach is also valuable for evaluation of potential drugs in vivo, therapy response can be compared in the same animal before drug treatment. Safety and toxicology studies have been completed, and we are progressing [11C]6 forward for evaluation as the first HDAC PET radiotracer and a novel class of epigenetic imaging probes in humans.

**EXPERIMENTAL SECTION**

**General Methods and Materials.** All reagents and solvents were of ACS-grade purity or higher and used without further purification. NMR data were recorded on a Varian 500 MHz magnet and were reported in ppm units downfield from trimethylsilane. Analytical separation was conducted on an Agilent 1100 series HPLC fitted with a diode-array detector, quaternary pump, vacuum degasser, and autosampler. Mass spectrometry data were recorded on an Agilent 6310 ion trap mass spectrometer (ESI source) connected to an Agilent 1200 series HPLC with quaternary pump, vacuum degasser, diode-array detector, and autosampler. The precursor and compound 6 were synthesized (from Sai Life Sciences Ltd.) with >98% purity, as determined by a high-pressure liquid chromatography (HPLC) system (YMC TRIART C-18 (150 mm × 4.6 mm × 3 u) mobile phase: A: 0.05% TFA in water/B: 0.05% TFA in acetonitrile. Flow rate: 1.0 mL/min. Gradient: 15% B to 95% B in 8.0 min, hold until 9.5 min, 15% B in 13.0 min hold until 15.0 min. The quantitative NMR test were conducted by Sai Life Sciences Ltd., and 1,4-dimethoxybenzene was used as the reference. [11C]CO₂ (1.2 Ci) was obtained via the 14N(p, α)11C reaction on nitrogen with 2.5% oxygen, with 11 MeV protons (Siemens Eclipse cyclotron), and trapped on molecular sieves in a TRACERlab FX-MeI synthesizer (General Electric). [11C]CH₄ was obtained by the reduction of [11C]CO₂ in the presence of Ni/ hydrogen at 350 °C and recirculated through an oven containing I₂ to produce [11C]CH₄ via a radical reaction.

All animal studies were carried out at Massachusetts General Hospital (PHS Assurance of Compliance no. A596-01). The Subcommittee on Research Animal Care (SRAC) serves as the Institutional Animal Care and Use Committee (IACUC) for the Massachusetts General Hospital (MGH). SRAC reviewed and approved all procedures detailed in this paper.

PET-MR imaging was performed in anesthetized (ketamine, isoflurane) baboon (Papio anubis) to minimize discomfort. Highly trained animal technicians monitored animal safety throughout all procedures, and veterinary staff were responsible for daily care. All animals were socially housed in cages appropriate for the physical and behavioral health of the individual animal. Animals were fed thrice per diem, with additional nutritional supplements provided as prescribed by the attending veterinarian. Audio, video, and tactile enrichment was provided on a daily basis to promote psychological well-being. Non-human primates were euthanized to accomplish the research presented.

PET-CT imaging was performed in anesthetized (isoflurane) rats (Sprague–Dawley) to minimize discomfort. Highly trained animal technicians monitored animal safety throughout all procedures, and veterinary staff were responsible for daily care. All animals were socially housed in cages appropriate for the physical and behavioral health of the individual animal. Animals were given unlimited access to food and water, with additional nutritional supplements provided as prescribed by the attending veterinary staff. Animals were euthanized at the end of the study using sodium pentobarbital (200 mg/kg, ip).

**Chemical Synthesis.** (E)-Methyl 3-((3r,5r,7r)-adamantan-1-ylmethylamino)methyl)acrylate (3). Adamantan-1-ylmethanamine (1) (1g, 6.0 mmol) and (E)-methyl 3-(4-formylphenyl)acrylate (2) (1 g, 5.3 mmol) was dissolved in MeOH (30 mL), and the mixture was stirred at room temperature for 2 h. Sodium borohydride (0.61g, 16 mmol) was then added, and the suspension was stirred overnight at room temperature. The white precipitate was filtered and dried to obtain the product 3 (1.35 g, yield: 75%). 1H NMR (500 MHz, CDCl₃): δ 7.69 (d, J = 16 Hz, 1H), 7.48 (d, J = 7 Hz, 2H), 7.35 (d, J = 7 Hz, 2H), 6.43 (d, J = 16 Hz, 1H), 3.81 (s, 2H), 3.80 (s, 3H), 2.23 (s, 3H), 1.96 (s, 3H), 1.63–1.73 (m, 6H), 1.53 (s, 6H); 13C NMR (125 MHz, CDCl₃): 167.55, 144.78, 143.81, 132.87, 128.35 (2C), 128.08 (2C), 117.10, 62.15, 54.28, 51.65, 40.85 (3C), 37.24 (3C), 33.49, 28.48 (3C); LC-MS calculated for C₂₈H₂₈N₂O₂ expected [M⁺]: 393.2; Found [M + H⁺]: 340.3.

(E)-3-3-((3r,5r,7r)-Adamantan-1-ylmethylamino)methyl)-N-hydroxyacrylamide (4). A solution of 3 (0.5 g, 1.5 mmol) in MeOH/THF (5 mL/5 mL) at 0 °C was added NH₄OH (50% aq solution, 3 mL) followed by 1 M NaOH (2 mL). The mixture was stirred at 0 °C for 2 h, warmed to room temperature, and stirred for 2 h. Acidification with 1 M HCl to pH 7–8 (pH paper) resulted in product precipitation. The precipitate was filtered and dried to obtain 4 (0.2 g, 40%) as white solid. 1H NMR (500 MHz, CDCl₃): δ 7.69 (d, J = 16 Hz, 1H), 7.39 (d, J = 7.5 Hz, 2H), 3.90 (d, J = 7.5 Hz, 2H), 6.42 (d, J = 16 Hz, 1H), 3.80 (s, 3H), 3.54 (s, 2H), 2.19 (s, 3H), 2.10 (s, 2H), 1.95 (s, 3H), 1.62–1.73 (m, 6H), 1.53 (s, 6H); 13C NMR (125 MHz, CDCl₃): 164.92, 141.31, 139.69, 133.75, 128.61 (2C), 127.41 (2C), 116.88, 71.09, 61.08, 53.31, 40.41 (3C), 36.77 (3C), 32.84, 28.48 (3C); LC-MS calculated for C₂₈H₂₈N₂O₂ expected [M⁺]: 393.2; Journal of Medicinal Chemistry 2014, 57, 7999–8009

dx.doi.org/10.1021/jm500887z J. Med. Chem. 2014, 57, 7999–8009
DNase digestion (trypsin: Cellgro no. 25-052-Cl; DNase: Sigma no. for 2 h. Acidification and μ HDAC inhibitor LBH-589 (panobinostat) with a mM HEPES (pH 7.4), 100 mM KCl, 0.01% BSA, and 0.001% Tween-20 was stirred at 0 °C (50% aq solution, 3 mL) followed by 1 M NaOH (2 mL). The mixture was filtered and dried to obtain 0.29 g, yield: 55% as white solid. 1H NMR (500 MHz, MeOH-d4): δ 7.55 (d, J = 16 Hz, 1H), 7.52 (d, J = 7.5 Hz, 2H), 7.37 (d, J = 7.5 Hz, 2H), 6.47 (d, J = 16 Hz, 1H), 3.77 (s, 2H), 2.21 (s, 2H), 1.94 (s, 3H), 1.66–1.76 (m, 6H), 1.54–1.55 (m, 6H). 13C NMR (125 MHz, MeOH-d4): 164.93, 141.32, 134.16, 133.76, 128.62 (2C), 127.43 (2C), 116.8901, 61.08, 53.32, 40.42 (3C), 36.78 (3C), 32.74, 28.48 (3C). LC-MS calculated for C12H12O2N2: 211.0800, 208.07, 190.06, 172.06, 154.06 (3C), 136.06 (3C), 118.06, 100.06, 82.06, 64.06, 46.06 (3C), 38.06 (3C). NMR purity: 97.05%. Radiosynthesis of [11C]6. [11C]C6 was trapped in a TRACERlab FX-M synthesizer reactor (General Electric) preloaded with a solution of precursor (4) (1.0 mg) in dry DMSO (300 μL). The solution was stirred at 100 °C for 4 min, and water (1.2 mL) was added. The reaction mixture was purified by reverse phase semi-preparative HPLC (Phenomenex Luna 5 μm C8(2), 250 × 10 mm, 5.0 mL/min, 40% H2O + ammonium acetate (0.1 M)/60% CH3CN), and the desired fraction was collected. The final product was reformulated by loading onto a solid-phase exchange (SPE) C-18 cartridge, rinsing with 1 M NaOH aq (5 mL), eluting with EtOH (1 mL), and diluting with 50 μL acetic acid in saline (0.9%, 9 mL). The chemical and radiochemical purity of the final product was tested by analytical HPLC (Agilent Eclipse XDB-C18, 150 × 4.6 mm). The identity of the product was confirmed by analytical HPLC with additional co-injection of reference standard. The average time required for the synthesis from end of cyclotron bombardment to end of synthesis was 35 min. The average radiochemical yield was 3–5% (nondelay corrected to trapped [11C]C6). Chemical and radiochemical purities were ≥95% with a specific activity of 1.0 ± 0.2 Ci/μmol (EOb). Specific Activity of [11C]6. Specific radioactivity (SA) of [11C]6 was calculated from an analytical HPLC sample of 100 μL. A calibration curve of known mass quantity versus HPLC peak area (254 nm) was used to calculate the mass concentration value determined for the formulated [11C]6 solution, volume, and measured radioactivity. The identity of the mass peak assigned to [11C]6 was supported by a second HPLC injection, where [11C]6 was mixed with nonradioactive compound 6 and yielded a single peak. The calibration curve used is shown in Figure S1. Log D Determination. An aliquot (~50 μL) of the formulated radiotracer was added to a test tube containing 2.5 mL of octanol and 2.5 mL of phosphate buffer solution (pH 7.4). The test tube was mixed by vortex for 2 min and then centrifuged for 2 min to fully separate the aqueous and organic phase. A sample taken from the octanol layer (0.1 mL) and the aqueous layer (1.0 mL) was saved for radioactivity measurement. An additional aliquot of the octanol layer (2.0 mL) was carefully transferred to a new test tube containing 0.5 mL of octanol and 2.5 mL of phosphate buffer solution (pH 7.4). The previous procedure (vortex mixing, centrifugation, sampling, and transfer to the next test tube) was repeated until six sets of aliquot samples had been prepared. The radioactivity of each sample was measured in a well counter (PerkinElmer, Waltham, MA). The log D of each set of samples was derived by the following equation: log D = log (decay-
corrected radioactivity in octanol sample \( \times 10/ \) decay-corrected radioactivity in phosphate buffer sample).

**Plasma Protein Binding Assay.** An aliquot of radiotracer in saline (10 mL) was added to a sample of baboon or human plasma (0.8 mL). The mixture was gently mixed by repeated inversion and incubated for 10 min at room temperature. Following incubation a small sample (20 mL) was removed to determine the total radioactivity in the plasma sample \( (A_T) \). An aliquot of 0.2 mL of the plasma sample was placed in the upper compartment of a Centrifree tube (Amicon, Inc., Beverly, MA) and then centrifuged for 10 min. The upper part of the Centrifree tube was discarded, and an aliquot (20 mL) from the bottom part of the tube was removed to determine the amount of radioactivity that passed through the membrane \( (A_{\text{bound}}) \). Plasma protein binding was derived by the following equation: \% bound = \( \frac{A_{\text{bound}}}{A_T} \times 100 \). 

**Ex vivo Autoradiography.** Twenty μm thick sagittal rat brain sections were cut using a −20°C cryostat, thaw-mounted onto gelatin-coated slides, fixed in 4% paraformaldehyde containing 2% ethanol for 60 min at 4 °C, and washed 10 min in ice-cold 10 mM Tris-HCl, pH 7.4. Sections were then incubated at room temperature in a 50 mL bath containing either (i) 5% DMSO as control; (ii) unlabeled 6 (100 μM) or (iii) SAHA (100 μM) for 10 min; or (iv) CI-994 (100 μM) for 2 h to allow for slow HDAC binding kinetics known for benzamide compounds including CI-994. All incubation baths contained 10 mM Tris-HCl + 5% DMSO, pH 7.4. \[^{11}C\] was prepared as described, and 100 μCi was added to each bath. Following 10 min incubation at room temperature, sections were washed 2 x 1 min in 10 mM Tris-HCl (pH 7.4) and carefully wiped dry on absorbent towels. Sections were exposed for 1 h to a multisensitive phosphorscreen and developed using a Cyclone Plus phosphorimager (both from PerkinElmer). Resulting parent image was evaluated using ImageJ software (NIH) with JET color lookup table (LUT) with whole-image intensity adjusted to enrich red color in control sections. Individual images of sections were cropped using ImageJ with no additional adjustment to color levels/thresholds.

**Rodent PET-CT Acquisition and Post-Processing.** Male Sprague–Dawley rats were utilized in pairs, anesthetized with inhalational isoflurane (Forane) at 3% in a carrier of 1.5–2 L/min medical oxygen, and maintained at 2% isoflurane for the duration of the scan. The rats were arranged head-to-head in a Triumph Tri-modality PET/CT/SPECT scanner (Gamma Medica, Northridge, CA). Rats were injected standard references or vehicle via a lateral tail vein catheterization at the start of PET acquisition. Dynamic PET acquisition lasted for 60 min and was followed by computed tomography (CT) for anatomic coregistration. PET data were reconstructed using 3D-OSEM method resulting in a fwhm resolution of 4 mm. Attenuation correction was performed using data obtained during the 80 min PET scan after a second injection of [\(^{11}C\)]6, a second imaging experiment was carried out in which unlabeled 6 was co-administered intravenously at the start of acquisition. Both scans were carried out on the same animal on the same day, separated by 2.5 h. In both scans, 4–5 mCi of [\(^{11}C\)]6 was administered to the baboon. In order to evaluate the blocking of [\(^{11}C\)]6 by SAHA, an separate dual-injection study of [\(^{11}C\)]6 was performed. In that experiment continuous SAHA infusion (2 mg/mL at 0.16 mL/min) was started after 45 min of baseline scan with [\(^{11}C\)]6, and the infusion was continued during the 80 min PET scan after a second injection of [\(^{11}C\)]6. PET data were recorded in list mode, and reconstruction was performed using a 3D-OSEM method resulting in a fwhm resolution of 4 mm. Attenuation correction was performed using the aforementioned 2-point Dixon 3D VIBE MR-derived attenuation maps. Data of each 80 min scan were reconstructed for TAC analysis using the following framing: 12 x 10, 3 x 20, 4 x 30, and 15 x 300 s. For the dedicated self-blocking and SAHA blocking experiments, additional static PET data were reconstructed using data obtained between 40 and 80 min and 20–45 min, respectively, in order to visualize the effects of blocking in multiple organs.

**Baboon PET-MR Acquisition.** PET data were motion-corrected, spatially smoothed with a 2.5 mm fwhm Gaussian filter, and registered to the Black baboon brain atlas using JIP tools optimized for nonhuman primate data processing (www.nitrc.org/projects/ijip). Image registration was carried out on high-resolution MPRAGE MRI image using a 12 degree of freedom linear algorithm and a nonlinear algorithm to the atlas brain. The transformation was then applied to the simultaneously collected dynamic PET data.

**Kinetic modeling was carried out in PMOD (PMOD3.3, PMOD Technologies Ltd., Zurich, Switzerland).** VOIs were selected according to the Black baboon brain atlas. A common VOI mask was applied to both baboon scans. TACs were exported from the whole brain, cerebellum, primary motor cortex, putamen, thalamus, primary visual cortex, caudate, and white matter VOIs for analysis. A two-tissue compartmental model was used to estimate regional volume of
distribution ($V_d$) with a metabolite-corrected plasma TAC. Voxel-wise $V_d$ maps were calculated using a Logan plot from the dynamic PET data. The time until linearity of the plot was achieved and determined for each scan.

In addition, regional $K_i/k_i$ and $k_i/k_e$ values were also obtained from the baseline scans using a two-tissue compartmental model. It is known that

$$\frac{B_{\text{max}}}{K_d} = \frac{K_i}{k_i} \left(1 + \frac{k_i}{k_e}\right)$$

with the assumption that $K_e = 0.4 \mu M$ (assumed from ex vivo HDAC-complex $K_e$ measurement for SAHA, which exhibits a similar $IC_50$ in vitro activity-based assays we determined). Averaged $B_{\text{max}}$ from the selected VOIs was estimated to be $19.6 \pm 2.9 \mu M$ (mean ± SD).

**Plasma and Metabolite Analysis.** Arterial samples collected during imaging from the baboon were centrifuged to obtain plasma, which was then removed and placed in an automated gamma counter that was calibrated to the PET scanner. Metabolite analysis was conducted on a custom automated robot fitted with Phenomenex SPE Strata-X 500 mg solid phase extraction cartridges that were primed with ethanol (2 mL) and deionized water (20 mL). Protein precipitation was achieved by addition of plasma (300 µL) to acetonitrile (300 µL), which was centrifuged for 1 min to obtain protein-free plasma (PFP). $300 \mu L$ of PFP/acetonitrile solution was diluted into deionized water (3 mL), loaded onto the C18 cartridge, and removed of polar metabolites by centrifugation at 1500 rpm for 5 min, and 0.6 mL of clear supernatant was vortexed with 3 mL water and applied to Phenomenex SPE Strata-X cartridges, centrifuged for 1 min to obtain protein-free plasma (PFP). Protein precipitation was achieved by addition of plasma (300 µL) to acetonitrile (300 µL), which was centrifuged for 1 min to obtain protein-free plasma (PFP). $300 \mu L$ of PFP/acetonitrile solution was diluted into deionized water (3 mL), loaded onto the C18 cartridge, and removed of polar metabolites with 100% water. Next, a series of extractions were performed using water and acetonitrile in quantities: 95:S, 90:10, 85:15, 80:20, 70:30, 60:40, 30:70, and 100% acetonitrile at a volume of 4 mL. A control experiment was performed before metabolite analysis to determine the retention of the parent compound by injection of a small amount of $[11C]6$ onto a test series of extraction cartridges. Each sample was counted in a WIZARD2 Automatic Gamma Counter to determine the presence of radiolabeled metabolites.

**Brain Metabolite Analysis.** One rat under pentobarbital anesthesia ($50 \text{ mg/kg, ip}$) was administered 0.538 mCi of $[11C]6$ by tail vein injection in 0.7 mL and after 30 min, sacrificed by pentobarbital overdose (additional 150 mg/kg, ip), and followed by rapid decapitation. The brain was removed, sagitally hemisected, and homogenized in 2 mL acetonitrile. The resulting suspension was centrifuged at 1500 rpm for 5 min, and 0.6 mL of clear supernatant was vortexed with 3 mL water and applied to Phenomenex SPE Strata-X 500 mg solid phase extraction cartridges, washed, and fractionally eluted with water containing increasing proportions of acetonitrile (100:0, 95:5, 90:10, 85:15, 80:20, 70:30, 60:40, 30:70, 0:100). Each sample was counted in a WIZARD2 Automatic Gamma Counter to determine the presence of radiolabeled metabolites.

**ASSOCIATED CONTENT**

1. Supporting Information
   The results of off-target binding, mPET imaging in rodents and SAHA pretreated study in NHP were shown in Table S1, Figure S1–S6. This material is available free of charge via the Internet at http://pubs.acs.org.

**AUTHOR INFORMATION**

Corresponding Author
*Telephone: 617-726-6596; E-mail: hooker@nmr.mgh.harvard.edu.

Notes
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

C.W. and H.Y.W. are supported by the Harvard/ MGH Nuclear Medicine Training Program from the Department of Energy (DE-SC0008430). Research was supported by the National Institute of Drug Abuse (NIDA) of the National Institutes of Health under grant numbers R01DA030321 (J.M.H.; S.J.H) with additional support under grant R01DA028301 (S.J.H.). This research was carried out at the Athinoula A. Martinos Center for Biomedical Imaging at the Massachusetts General Hospital, using resources provided by the Center for Functional Neuroimaging Technologies, P41EB015896, a P41 Regional Resource supported by the National Institute of Biomedical Imaging and Bioengineering (NIBIB), National Institutes of Health. This work also involved the use of instrumentation supported by the NIH Shared Instrumentation Grant Program and/or High-End Instrumentation Grant Program; specifically, grant nos: S10RR017208, S10RR026666, S10RR022976, S10RR019933, and S10RR029495. The authors are grateful to Joe Mandeville and Helen Deng as well as the Martinos Center radiopharmacy and imaging staff (Grae Arabasz, Shirley Hsu, Stephen Carlin, Chris Moseley, Nathan Schauer, Ehimen Asaborhale, Judit Sore) for help with nonhuman primate experiments. HDAC activity screening was enabled by a Caliper assay developed by Jennifer Gale and Yan-Ling Zhang at the Broad Institute.

**ABBREVIATIONS USED**

HDACs, histone deacetylases; CNS, Center for Nanoscale Systems; PET, positron emission tomography; PPB, plasma protein binding; DAT, dopamine transporter; P-gp, P-glycoprotein; NHP, nonhuman primate; GWAS, genome-wide association studies; SNPs, single nucleotide polymorphisms; tPSA, total polar surface area; TAC, time—activity curve

**REFERENCES**


