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Original Article

Design, synthesis, and evaluation of hydroxamic acid-based molecular probes for *in vivo* imaging of histone deacetylase (HDAC) in brain

Changning Wang¹, Thomas E Eessalu², Vanessa N Barth², Charles H Mitch², Florence F Wagner³, Yijia Hong⁴, Ramesh Neelamegam¹, Frederick A Schroeder⁵, Edward B Holson³, Stephen J Haggarty⁵, Jacob M Hooker¹

¹Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, Charlestown, MA 02129, USA; ²Eli Lilly & Co., Indianapolis, IN 46285, USA; ³Stanley Center for Psychiatric Research, Broad Institute of Harvard and MIT, 7 Cambridge Center, Cambridge, MA 02142, USA; ⁴Department of Molecular and Cell Biology, University of California, Berkeley, CA 94720, USA; ⁵Chemical Neurobiology Laboratory, Departments of Neurology and Psychiatry, Center for Human Genetic Research, Massachusetts General Hospital, 185 Cambridge Street, Boston, MA 02114, USA

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Abstract: Hydroxamic acid-based histone deacetylase inhibitors (HDACis) are a class of molecules with therapeutic potential currently reflected in the use of suberoylanilide hydroxamic acid (SAHA; Vorinostat) to treat cutaneous T-cell lymphomas (CTCL). HDACis may have utility beyond cancer therapy, as preclinical studies have ascribed HDAC inhibition as beneficial in areas such as heart disease, diabetes, depression, neurodegeneration, and other disorders of the central nervous system (CNS). However, little is known about the pharmacokinetics (PK) of hydroxamates, particularly with respect to CNS-penetration, distribution, and retention. To explore the rodent and non-human primate (NHP) brain permeability of hydroxamic acid-based HDAC inhibitors using positron emission tomography (PET), we modified the structures of belinostat (PXD101) and panobinostat (LBH-589) to incorporate carbon-11. We also labeled PCI 34051 through carbon isotope substitution. After characterizing the *in vitro* affinity and efficacy of these compounds across nine recombinant HDAC isoforms spanning Class I and Class II family members, we determined the brain uptake of each inhibitor. Each labeled compound has low uptake in brain tissue when administered intravenously to rodents and NHPs. In rodent studies, we observed that brain accumulation of the radiotracers were unaffected by the pre-administration of unlabeled inhibitors. Knowing that CNS-penetration may be desirable for both imaging applications and therapy, we explored whether a liquid chromatography, tandem mass spectrometry (LC-MS-MS) method to predict brain penetrance would be an appropriate method to pre-screen compounds (hydroxamic acid-based HDACi) prior to PET radiolabeling. LC-MS-MS data were indeed useful in identifying additional lead molecules to explore as PET imaging agents to visualize HDAC enzymes *in vivo*. However, HDACi brain penetrance predicted by LC-MS-MS did not strongly correlate with PET imaging results. This underscores the importance of *in vivo* PET imaging tools in characterizing putative CNS drug lead compounds and the continued need to discover effect PET tracers for neuroepigenetic imaging.

Keywords: Hydroxamic acid, HDAC inhibitors, epigenetic, PET, brain, imaging

Introduction

Histone proteins and their associated DNA together comprise nucleosomes, the fundamental unit of chromatin structure and the structural base for DNA condensation. Covalent chemical modification of histones via processes such as acetylation, methylation, ubiquitination and phosphorylation [1], play a critical role

in the dynamic regulation of gene expression through chromatin remodeling and modulating transcription factor binding.

Histone acetylation is regulated by the opposing actions of two enzyme classes, histone acetyltransferases (HATs) and histone deacetylases (HDACs) [2-4]. HDAC enzymes are divided into four different classes based on sequence

HDAC imaging

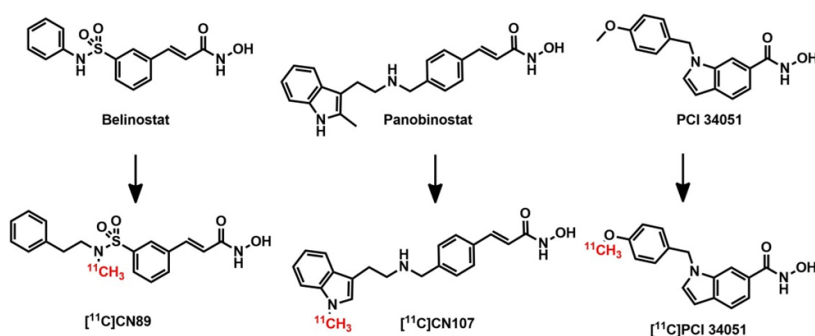


Figure 1. Structures of selected HDAC inhibitors on clinical trials and the potential PET radiotracers derived from these HDACis.

homology, cellular localization and phylogenetic relationships to yeast homologues [5]: class I (HDACs 1, 3, 8), class IIa (HDACs 4, 5, 7, 9), class IIb (HDACs 6, 10), class III (SIRT1, 7), and class IV (HDAC 11). Classes I, II and IV are zinc dependent enzymes. Increases in histone acetylation causes relaxation of higher order chromatin structure and contributes to activation of gene expression [6]. Importantly, histone acetylation-mediated changes in gene expression are cell-type specific and outcomes range from necrosis, cytostasis, and apoptosis in cancerous cells to robust neuronal differentiation in neural precursors and enhancement of synaptogenesis [7, 8]. As such, deficiencies in histone acetylation and transcriptional dysfunction have been implicated in cancer pathology as well as in a number of neurodegenerative diseases including Huntington's [9-12], Parkinson's and Alzheimer's diseases [9, 13-15], amyotrophic lateral sclerosis [16, 17], spinal muscular atrophy [18] and stroke [13-15]. Clarifying the role of HDAC function in normal and disease biology has direct relevance to therapeutic development [19, 20].

HDAC inhibitors (HDACis) have emerged as promising drug candidates to restore the balance of HDAC and histone acetyl-transferase (HAT) enzymes in disease. Class I, II and IV HDAC enzymes are zinc dependent and can be inhibited by compounds with zinc-chelating moieties. These compounds comprise diverse structural classes [21-27] including the most widely-investigated, the hydroxamic acids [22]. Following the initial discovery that the hydroxamic acid, trichostatin A, was a strong inhibitor of HDAC targets ($K_i = 3.4$ nM) [28], research led to the development of suberoyl-anilide hydroxamic acid (SAHA, vorinostat) which was FDA-approved for the treatment of

cutaneous T-cell lymphomas (CTCL). This provided key evidence that HDAC inhibitors, including those hydroxamic acid-based structures, could have therapeutic potential.

Thus, cinnamic acid derivatives have been intensely investigated as HDAC inhibitors. Several compounds from this class have advanced into clinical

trials, including belinostat and panobinostat. Belinostat is a potent HDACi ($IC_{50} = 27$ nM), with the sulfonamide substitute in the *meta* position, and is undergoing phase II trials in solid tumors (ovarian, hepatocarcinoma, mesothelioma) [29]. Panobinostat, an almost equally potent HDACi ($IC_{50} = 37$ nM), is currently in phase II/III clinical trials for chronic myeloid leukemia, refractory CTCL, and multiple myeloma [30]. In addition to cinnamic acids, the phenyl hydroxamate, PCI 34051 is the most subtype selective HDAC inhibitor identified to date. This compound has a reported $IC_{50} = 10$ nM for HDAC8 - revealing greater than 100-fold selectivity over other HDAC subtypes [31]. Selective HDAC inhibition is increasingly used to clarify understanding of the biological role of HDAC subtypes [32, 33]. However, PCI 34051 remains underutilized as a highly selective HDAC inhibitor and could provide insight into the role of HDAC8. Despite their potential as therapeutic leads and tool compounds, little is known about how these three inhibitors impact HDAC targets in the living brain.

LC-MS-MS can be used to measure the brain penetration of a compound, although is invasive, requiring brain removal thereby limiting its application to pre-clinical models. Developing an imaging tool that permits detection and quantification of HDAC expression *in vivo* is critical to assess the efficacy of HDAC-targeted therapies and to clarify the understanding of the mechanism of HDAC enzyme dysfunction in disease. Positron emission tomography (PET) is an excellent tool for the *in vivo* quantification of HDAC biological processes as well as evaluation of the pattern of HDAC distribution in animals and human. A few fluorine-18 labeled compounds ($[^{18}F]$ FAHA [34], $[^{18}F]$ SAHA [35]) have been reported and demonstrate the

HDAC imaging

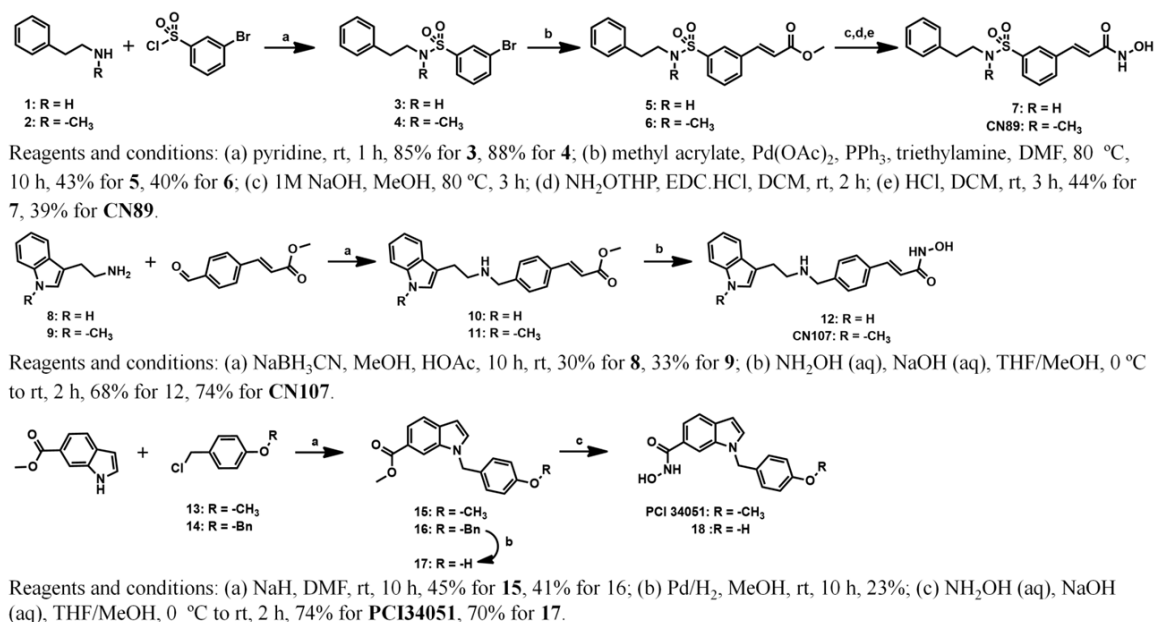


Figure 2. Synthesis of HDAC inhibitors and their precursors for carbon-11 labeling.

potential for *in vivo* HDAC imaging in animals, although to date, no *in vivo* imaging studies have evaluated the brain penetrance of hydroxamic acid-based HDACi [36]. Rodent studies have shown that the BBB penetrance of SAHA is very low, but as a class, the brain availability hydroxamic acids is largely unexplored [37].

In our experiments, we utilized *in vivo* PET imaging in rodent and non-human primate to characterize blood-brain barrier (BBB) penetration [38, 39] of select carbon-11 labeled hydroxamic acid-based HDAC inhibitors. We additionally compared BBB penetrance predicted by LC-MS-MS methods. The results of our findings are presented and discussed below.

Results

Chemical synthesis

To incorporate carbon-11, we modified the structures of belinostat and panobinostat, as shown in **Figure 1**. **PCI34051** has a methoxyl group and thus could be labeled without structural modification. The synthesis of the HDAC inhibitors and their carbon-11 labeling precursors are shown in **Figure 2**. Briefly, *N*-methyl-2-phenylethanamine was reacted with 3-bromobenzene-1-sulfonyl chloride to form intermediate **4**, which was then coupled with methyl

acrylate catalyzed by Pd(OAc)₂ to provide the methyl ester **6**. Methyl ester **6** was hydrolyzed with 1 M NaOH, then coupled with NH₂-OTHP, and converted to the target hydroxamate **CN89** after deprotection of THP in the presence of HCl. The synthesis of precursor **7** was synthesized by a similar route, starting from phenylethanamine. Reductive amination of 4-formylcinnamic methyl ester with a primary amines afforded methyl esters **10** and **11**. Methyl esters were treated with hydroxylamine (hydroxylamine, excessive sodium methoxide in methanol/THF) and converted to the target hydroxamates, **CN107** and its precursor **12**. Methyl 1*H*-indole-6-carboxylate was reacted with **13** or **14** in the presence of sodium hydride to afford intermediate **15** or **16**. Methyl ester **15** was treated with hydroxylamine to obtain **PCI 34051**. Its precursor **18** was achieved by hydrogenation, followed by treatment with hydroxylamine.

In vitro HDAC assay

The *in vitro* inhibitory activities of **CN89**, **CN107**, and **PCI 34051** were measured for each HDAC isoform HDAC1 through HDAC9 (**Table 1**). The IC₅₀ value for SAHA was measured in parallel as a reference. The synthesized belinostat analog **CN 89** showed low nanomolar IC₅₀ towards class-I HDAC isoforms (HDAC1-3) as well as toward class-II HDAC isoform (HDAC6). The pan-

Table 1. HDAC isoforms selectivity data for selected HDAC inhibitors

Compound	IC ₅₀ [nM]								
	HDAC1	HDAC2	HDAC3	HDAC4	HDAC5	HDAC6	HDAC7	HDAC8	HDAC9
SAHA	4	11	3	40200	8750	2.2	42800	1020	70000
CN89	5	32	3.4	500	10732	5	44488	150	16904
CN107	0.19	1.15	0.38	655	99	1.6	2044	1044	4849
PCI 34051	36400	1740	50300	-	70000	7390	70000	18.3	70000

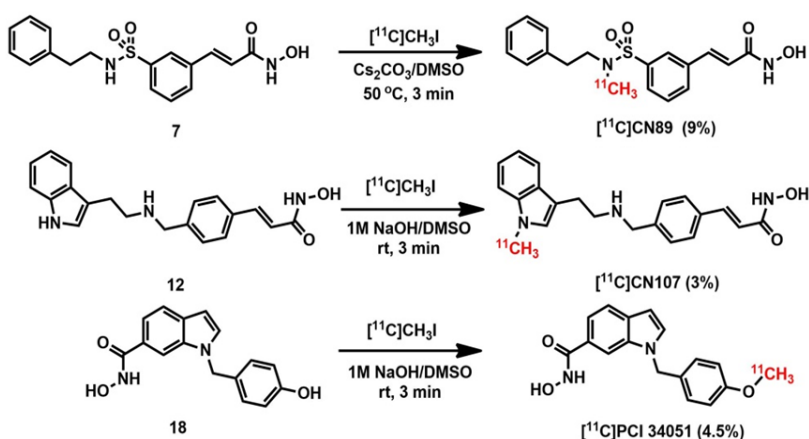


Figure 3. Radiosynthesis of [¹¹C]**CN89** (RCY: 9%, non-decay corrected to trapped [¹¹C]CH₃I with a specific activity 0.8±0.2 Ci/μmol (EOB)); [¹¹C]**CN107** (RCY: 3%, non-decay corrected to trapped [¹¹C]CH₃I with a specific activity 0.9±0.1 Ci/μmol (EOB)); and [¹¹C]**PCI 34051** (RCY: 4.5%, non-decay corrected to trapped [¹¹C]CH₃I with a specific activity 0.7±0.2 Ci/μmol (EOB)).

obinostat derivative, **CN107**, also showed low nanomolar IC₅₀ towards the same class-I HDAC isoforms, indicating that the methyl group we introduced did not significantly degrade the affinity or selectivity of these compounds. The IC₅₀ value of **PCI 34051** for HDAC8, using an activity assay different than that previously described [40, 41], was found to be 18.2 nM, which is greater than 100-fold selectivity over each of the other HDAC isoforms.

Radiosynthesis of selected HDAC inhibitors

The synthesis of the candidate radiotracers was accomplished using precursors in DMSO with [¹¹C]methyl iodine ([¹¹C]CH₃I) as outlined in **Figure 3**. [¹¹C]CH₃I was trapped in a TRACERlab FX-M synthesizer reactor preloaded with a solution of precursor **7** (1.0 mg) and Cs₂CO₃ (6.0 mg) for **CN89**; precursor **12** (1.0 mg) and 10 μl of 1 M NaOH for **CN107**; precursor **18** (1.0 mg) and 10 μl of 1 M NaOH for **PCI 34051** in dry DMSO (300 μL). The solution was stirred under pressure at 50 °C (**CN89**) or room temp (**CN107** and **PCI 34051**) for 3 min and then water (1.2

mL) was added. The reaction mixture was purified by reverse phase semi-preparative HPLC and the desired fraction was collected. The final product was reformulated by loading water-diluted eluent onto a solid-phase exchange (SPE) C-18 cartridge. The SPE was rinsed with H₂O (5 mL) and the isolated material was eluted from the SPE with EtOH (1 mL followed by saline (0.9%, 9 mL). The chemical and radiochemical purity of the final product was determined by analytical HPLC.

The identity of the product was confirmed by analytical HPLC by co-elution comparison to a reference standard. The average time required for the synthesis from end of cyclotron bombardment to end of synthesis was 34 min (**CN89**), 37 min (**CN107**) and 36 min (**PCI 34051**). The radiochemical yield was 9% (**CN89**), 3% (**CN107**) and 4.5% (**PCI 34051**) (non-decay corrected relative to trapped [¹¹C]CH₃I). Chemical and radiochemical purities were ≥ 95% for all radiotracers.

PET imaging in rodents and NHPs

Using PET-CT, we determined that all labeled compounds exhibited very poor initial BBB penetration and low brain uptake over the scanning time (60 min) when administered intravenously to rats (0.9-1.1 mCi per scan), as shown in **Figure 4**. A concentration of less than 0.15 %ID/cc was distributed in the brain tissue after administration of [¹¹C]**CN89** and [¹¹C]**CN107**. We also conducted the PET imaging study with the pretreatment of reference standards (2

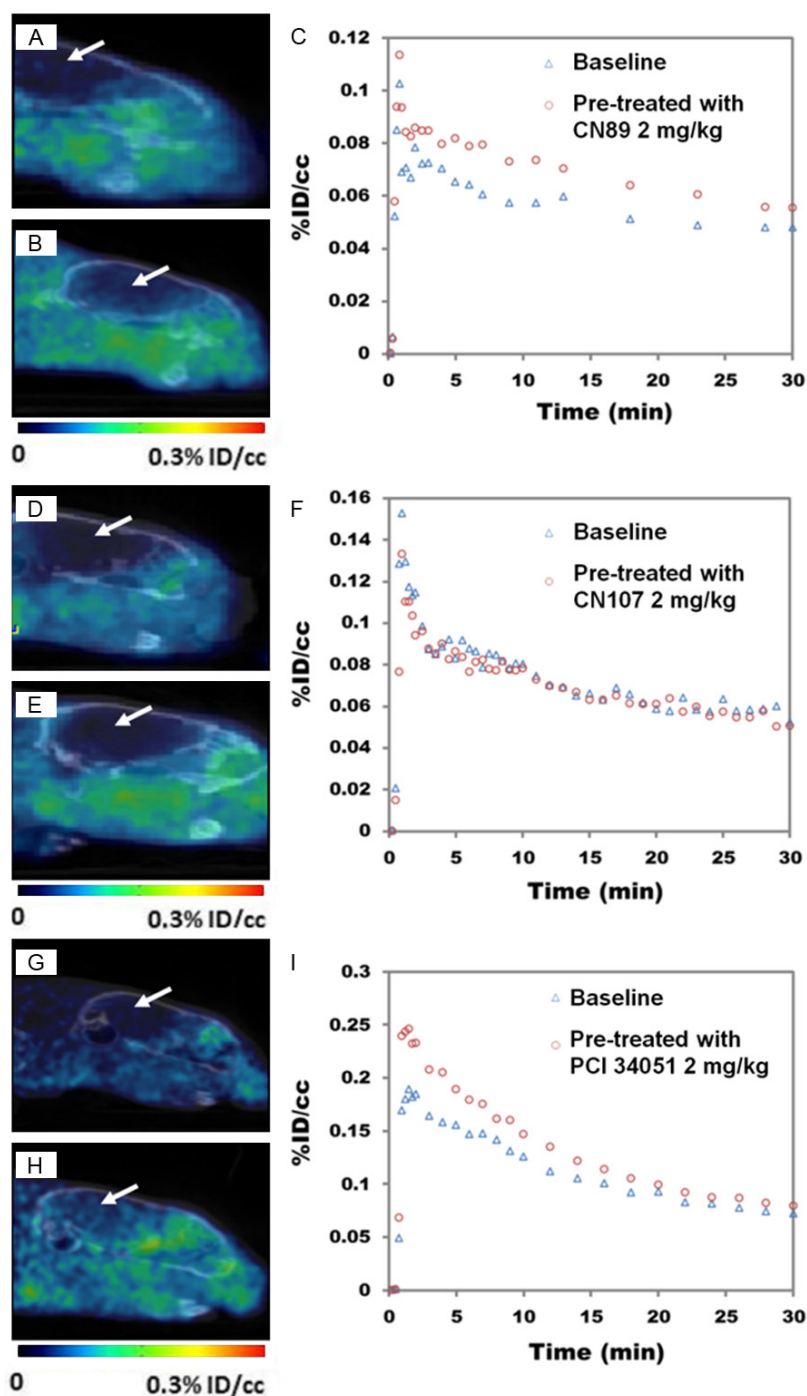


Figure 4. Rodent imaging experiments with radiotracers. Summed PET images (1-60 min) following injection of $[^{11}\text{C}]\text{CN89}$ (A), $[^{11}\text{C}]\text{CN107}$ (D) and $[^{11}\text{C}]\text{PCI 34051}$ (G) baseline scans; summed PET-CT images (1-60 min) images acquired following pretreatment with corresponding unlabeled inhibitors (B: **CN89**; E: **CN107**; H: **PCI 34051**) (2 mg/kg, iv). Images are dose corrected. Whole-brain time-activity curves generated from rodent PET imaging data (0-30 min) for $[^{11}\text{C}]\text{CN89}$ (C), $[^{11}\text{C}]\text{CN107}$ (F) and $[^{11}\text{C}]\text{PCI 34051}$ (I).

mg/kg); however, we did not observe a change in permeability or retention after pretreatment.

To further investigate the brain permeability of the carbon-11 labeled compounds, we conducted imaging in *Papio anubis* baboons. Using PET-MRI, we further determined that $[^{11}\text{C}]\text{CN89}$, $[^{11}\text{C}]\text{CN107}$ and $[^{11}\text{C}]\text{PCI 34051}$ exhibited very poor BBB penetration and low brain uptake over the scanning time (80 min) when the radiotracers (4-5 mCi) were administered intravenously, **Figure 5**. Coregistration of the PET image with an MRI of the same animal indicated that some radioactivity indeed partitioned into brain tissue, albeit at low levels.

Brain uptake test with LC-MS-MS method

According to the LC-MS-MS results, **CN89** showed higher standardized uptake values (SUV) and brain to plasma ratio than **CN107** and **PCI 34051**, which showed low uptake in the brain; as a subsequent LC-MS-MS screen, we chose three additional compounds (**19**, **20** and **21**) (IC_{50} : **19**: HDAC1 = 19.2 nM, HDAC2 = 109 nM, HDAC3 = 79.3 nM; **20**: HDAC1 = 165 nM, HDAC2 = 660 nM, HDAC3 = 90 nM; **21**: HDAC1 = 56.1 nM, HDAC2 = 53.7 nM, HDAC3 = 7.1 nM) to evaluate for brain uptake. We chose these compounds based on their hydroxamic acid structure. Compounds **19** and **20** showed low SUV (0-4% in hippocampus, **Table 2**) indicating they are likely not brain penetrant.

Compound **21** showed high SUV (in hippocampus) and brain (hippocampus) to plasma ratio

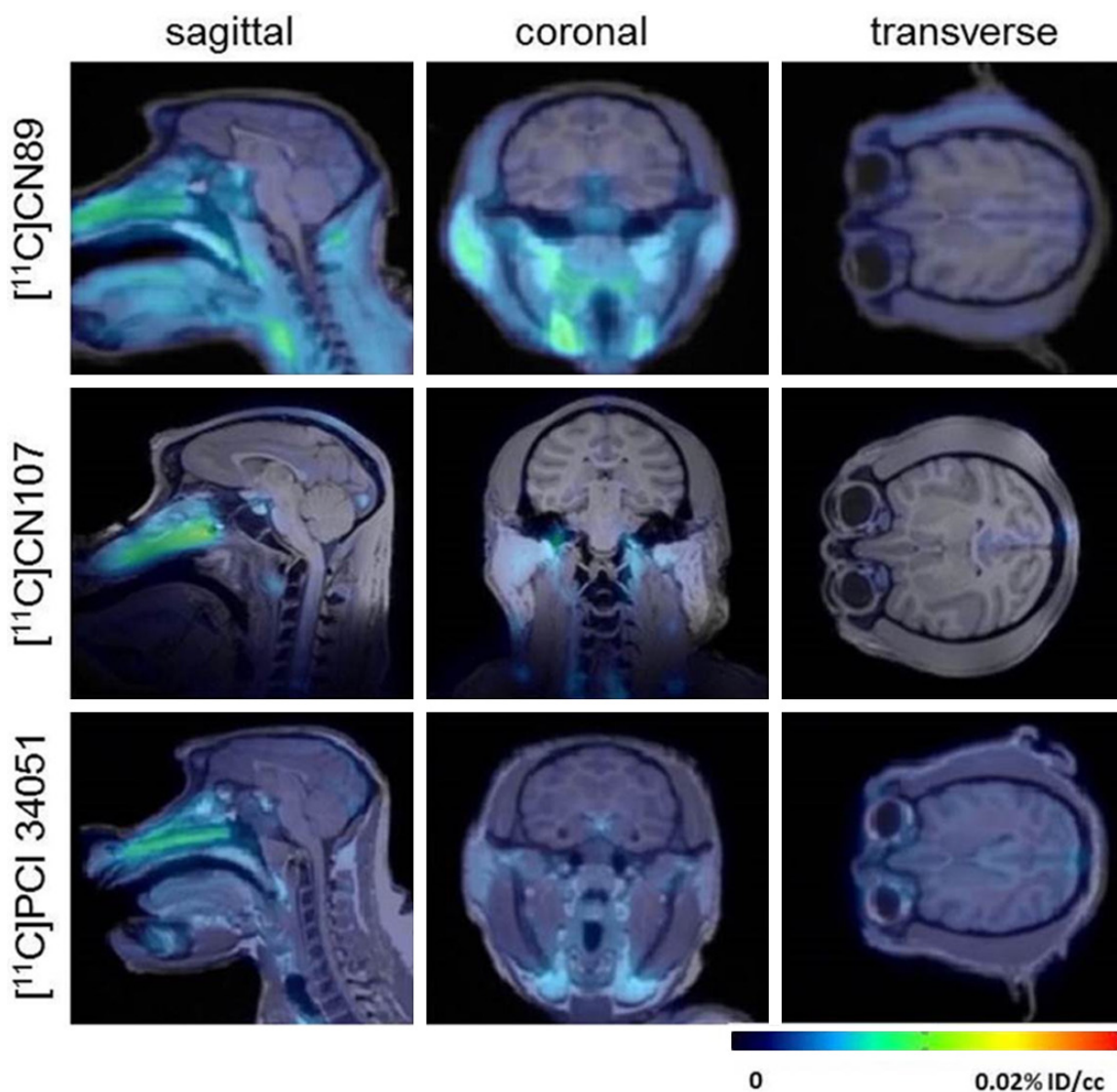


Figure 5. PET-MRI Imaging (baboon brain). Summed PET images (0-80 min) superimposed with a MEMPRAGE-MRI of the brain from the same baboon, following injection of radiotracers (4-5 mCi/baboon). Top row: $[^{11}\text{C}]\text{CN89}$; middle row: $[^{11}\text{C}]\text{CN107}$; bottom row: $[^{11}\text{C}]\text{PCI 34051}$.

(Table 2) indicating CNS penetration of this compound.

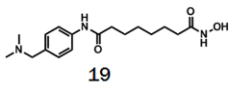
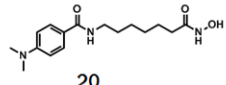
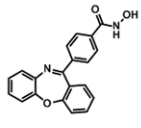
Discussion

HDACs play an important role in diseases, including, but not limited to, brain disorders, heart disease and cancers, but there is no method to measure the HDAC expression in human with such diseases and monitor the disease progress and evaluate the therapeutics. To measure and quantification of HDAC expression non-invasive *in vivo*, PET would be an ideal tool, however, there is still no validated PET radiotracer available for HDAC imaging, particu-

larly in the brain. We chose some HDAC inhibitors, current in the clinical trials, to incorporate the positron emission isotopes to test the brain permeability of these inhibitors. After structural modifications, the compounds are easy to incorporate with carbon-11 and remain the high binding towards HDACs.

To evaluate their brain permeability, we conduct PET imaging with rodents and NHPs. The summed PET-CT images showed that the radioactivity within the skull from all the three tracers is likely outside of the BBB and represents the blood pool within the rats brain (Figure 4). The NHP imaging results were consistent with

Table 2. Physiochemical properties of selected hydroxamic acid HDAC inhibitors and the evaluation of CNS permeability with LC-MS-MS

Compound	Molecular Weight	Log <i>P</i>	tPSA	%SUV @20 min	B/P @20 min
 19	321.41	1.74	81.67	0	0
 20	307.39	2.07	81.67	4	0.36
CN107	349.43	2.66	64.6	8	1
PCI 34051	296.32	2.61	61.8	30	0
CN89	360.43	2.03	86.71	77	6
 21	330.34	3.64	70.92	222	4.5

SUV = Standardized Uptake Volume (% Tracer conc. in Hippocampus @20 min). B/P = Brain to Plasma ratio (Hippocampus/Plasma).

the PET experiments we conducted in rodents, showing the limited brain uptake with these radiolabeled compounds. Additional experiments will be needed both *in vitro* and *in vivo* to determine the reason these hydroxamic acid HDACis have poor CNS permeability.

Given that PET imaging is a relatively slow and costly means of 'screening' HDAC imaging candidates, we additionally utilized LC-MS-MS as an established and low-cost method to identify lead molecules with good BBB penetration and specific binding (at microdoses). LC-MS-MS has been used for the assessment of brain tracer distribution of dopamine D2, serotonin 2A and NK-1 receptors [42]. Using these published methods, our LC-MS-MS results indicated that **CN89** showed higher standardized uptake values (SUV) and brain to plasma ratio than **CN107** and **PCI 34051**; however, via *in vivo* PET imaging, [^{11}C]**PCI 34051** had the highest %ID/cc compared to [^{11}C]**CN89** and [^{11}C]**CN107**. One possibility why the PET and LC-MS-MS data were not consistent is that the injected mass of unlabeled compounds for LC-MS-MS detection is at least 10-fold larger (in 2-3 microgram range) compared with nanogram amounts for PET imaging (200-300 nanograms). Thus, the BBB may only effectively prevent a small amount (nanograms) of compound from reaching the brain, resulting in a lack of CNS tracer uptake as visualized by PET. Experiments to test this directly are not feasible as it is not ethical to deliver microgram quantities of radiolabeled compound for *in vivo* PET imaging nor is

it possible to detect nanogram amounts of compound using current LC-MS-MS methods. Additional screening of HDACis with LC-MS-MS method indicates that compound **21** has potential to be used as new CNS radiotracers and HDAC inhibitors.

Overall, these results still indicate that LC-MS-MS could be used as a preliminary screening tool for the CNS radiotracer development as, compared to PET imaging, it is a low-cost and high-throughput technique. However PET imaging provides a unique advantage as a non-invasive technique that can provide a visual representation of a labeled compound in a living brain.

Conclusions

In summary, we successfully synthesized and characterized binding affinity for [^{11}C]hydroxamic acid-based HDAC inhibitors **CN89**, **CN107**, and **PCI 34051**. PET studies performed in conjunction with CT and MRI evaluated the brain uptake of these radiotracers, demonstrating poor BBB penetration in rats as well as in baboon. Our PET imaging data indicate these compounds are not effective tracers for diseases localized in the CNS. However our experiments have not ruled out the potential utility of these candidate probes for imaging and therapy in non-CNS diseases, such as peripheral cancers. The development of CNS-penetrant HDAC imaging probes and the evaluation of [^{11}C]**CN89**, [^{11}C]**CN107** and [^{11}C]**PCI 34051** as

peripheral PET imaging probes are currently underway.

Supporting information

The section discussing materials and methods is included in SI. This section describes chemical synthesis, radiolabeling used in this study. Assay procedures for determination of *in vitro* enzymatic assay for histone deacetylases, LC-MS-MS method and animal imaging experiments are also detailed in SI.

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Disclosure of conflict of interest

None.

Address correspondence to: Dr. Jacob M Hooker, Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, 149 13th Street Suite 2301, Charlestown, MA 02129, USA. Tel: 617-726-6596; Fax: 617-726-7422; E-mail: hooker@nmr.mgh.harvard.edu

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