

# In Silico-Guided Rational Drug Design and Semi-synthesis of C(2)-Functionalized Huperzine A Derivatives as Acetylcholinesterase Inhibitors

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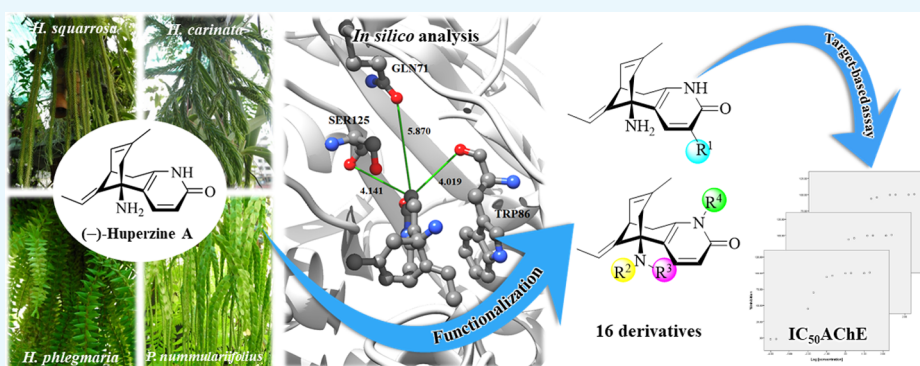
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**ABSTRACT:** Huperzine A (**1**, Hup A), a lycodine-type *Lycopodium* alkaloid isolated from Thai clubmosses *Huperzia squarrosa* (G. Forst.) Trevis., *H. carinata* (Desv. ex. Poir.) Trevis., *H. phlegmaria* (L.), and *Phlegmariurus nummularifolius* (Blume) Chambers (Lycopodiaceae), exerts inhibitory activity on acetylcholinesterase, a known target for Alzheimer's disease therapy. This study investigated the structure–activity relationship of C(2)-functionalized and *O*- or *N*-methyl-substituted huperzine A derivatives. *In silico*-guided screening was performed to search for potential active compounds. Molecular docking analysis suggested that substitution at the C(2) position of Hup A with small functional groups could enhance binding affinity with AChE. Consequently, 12 C(2)-functionalized and four *O*- or *N*-methyl-substituted compounds were semi-synthesized and evaluated for their *ee*AChE and *eq*BChE inhibitory activities. The result showed that 2-methoxyhuperzine A (**10**) displayed moderate to high *ee*AChE inhibitory potency ( $IC_{50} = 0.16 \mu\text{M}$ ) with the best selectivity over *eq*BChE (selectivity index = 3633). Notably, this work showed a case of which computational analysis could be utilized as a tool to rationally screen and design promising drug molecules, getting rid of impotent molecules before going more deeply on labor-intensive and time-consuming drug discovery and development processes.

## INTRODUCTION

Alzheimer's disease (AD), a dementia-related neurodegenerative brain disorder, is characterized by progressive cognitive impairment according to increments in atrophy or loss of neurons and synapse interneurons.<sup>1</sup> AD ranks in the top-five leading causes of global disability-adjusted life-years in patients aged 75 years and older.<sup>2</sup> Alzheimer's Disease International estimates that there are over 50 million people globally suffering from dementia and the number tends to increase to 152 million by 2050.<sup>3</sup> The characteristic pathologic hallmark of AD relates to cholinergic neuronal death in basal forebrain, neocortex, and hippocampus regions caused by deposition of amyloid-beta ( $A\beta$ ) plaque and neurofibrillary tangle (NFT) in the brain.<sup>4</sup>

Acetylcholinesterase (AChE) is an essential enzyme that plays a key role in controlling the acetylcholine (ACh) neurotransmitter level, affecting cholinergic neurotransmis-

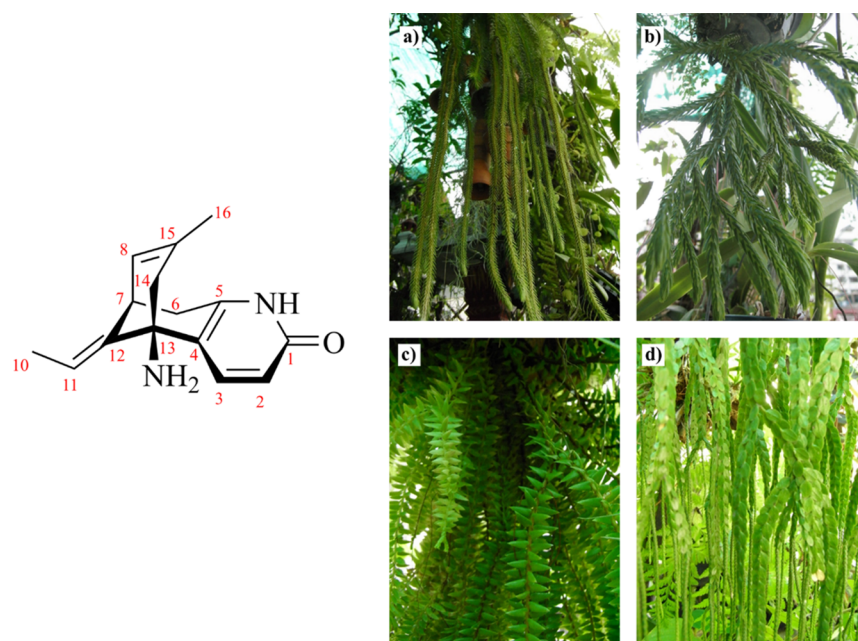
sion.<sup>5</sup> Boosting the level of ACh by AChE inhibitors is an effective symptomatic treatment of mild to moderate AD, approved by USFDA.<sup>6</sup> However, in advanced stages of AD, the use of AChE inhibitors is limited due to peripheral cholinergic side effects caused by nonselective inhibition of butyrylcholinesterase (BChE).<sup>7,8</sup> Thus to improve the efficacy and safety of symptomatic AD treatment, the development of central nervous system-selective AChE inhibitors without peripheral side effects is crucial.

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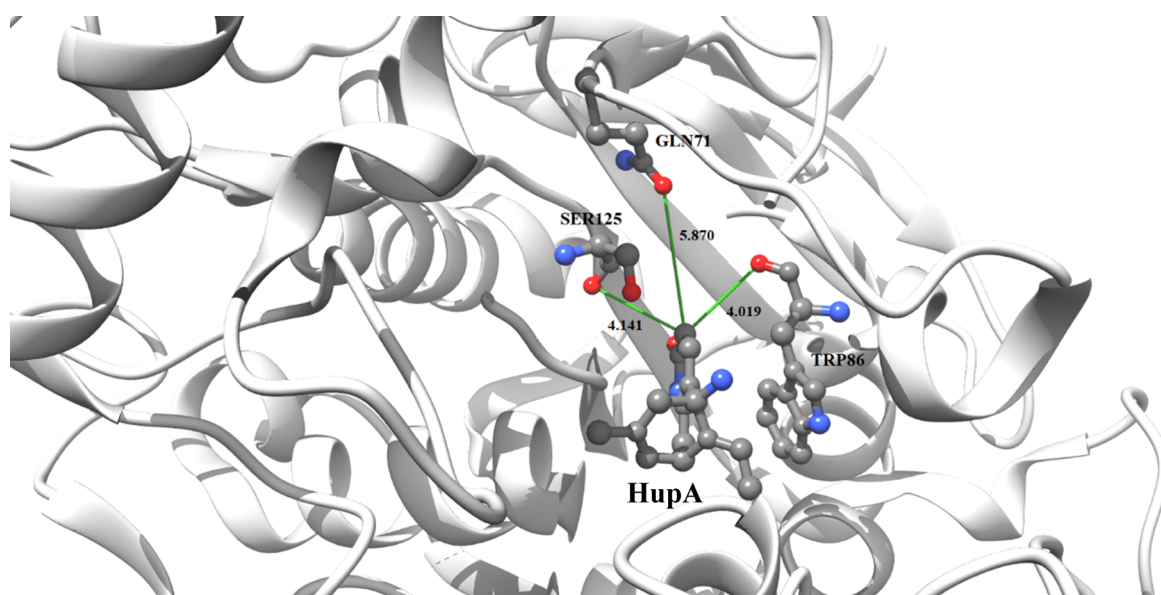
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**Figure 1.** Structure of (–)-huperzine A (**1**) and club mosses (a) *H. squarrosa*, (b) *H. carinata*, (c) *H. phlegmaria*, and (d) *P. nummulariifolius*.

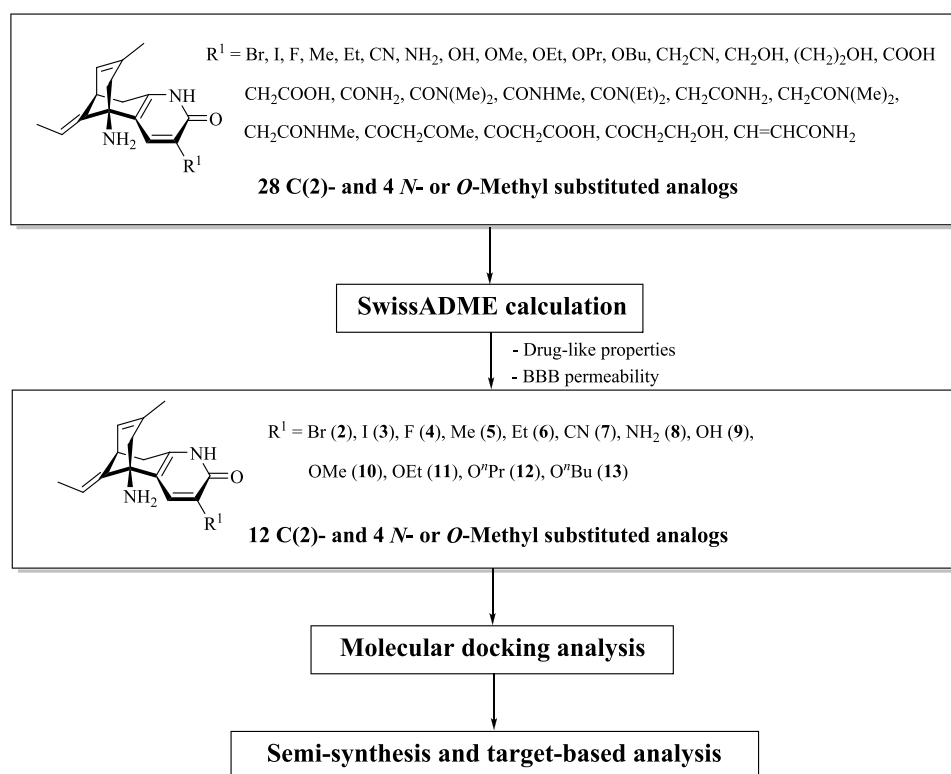


**Figure 2.** Molecular docking of HupA with AChE (4EY5) from BUDE and Sire Waterswap.

(–)-Huperzine A (HupA (**1**), [Figure 1](#)) is a lycodine-type *Lycopodium* alkaloid that was first isolated from Chinese clubmoss *Huperzia serrata* (family Lycopodiaceae). HupA is a potent inhibitor of AChE ( $IC_{50} = 0.02 \mu\text{M}$  toward *hAChE*)<sup>9</sup> and has been used (as a dietary supplement) to treat mild AD.<sup>10</sup> Although clinical studies still showed ambiguous results on the improvement of cognitive function in AD patients,<sup>11,12</sup> the core structure of HupA is a promising lead moiety, which can be derivatized for the development of AChE inhibitors with improved selectivity and efficacy. In our recent studies, (–)-HupA (**1**) was isolated from alkaloid-rich fractions clubmosses *Huperzia squarrosa* (G. Forst.) Trevis., *H. carinata* (Desv. ex Poir.) Trevis., *H. phlegmaria* (L.), and *Phlegmariurus nummulariifolius* (Blume) Chambers (Lycopodiaceae) in large quantities.<sup>13–15</sup> With HupA in hand, chemical modifications

were performed on the pyridone ring moiety by *in silico*-guided screening for potential active compounds as AChE inhibitors.

Our preliminary docking was carried out to visualize the key interactions between HupA and human AChE by using Bristol University Docking Engine (BUDE) and Sire Waterswap molecular simulation. Using the BUDE, HupA was docked into the crystal structures of recombinant human AChE (*hAChE*) in all three forms: *hAChE* in the apo state (PDB ID: 4EY4), *hAChE* complexing with HupA (PDB ID: 4EY5), and *hAChE* complexing with donepezil (PDB ID: 4EY7). BUDE managed to dock HupA into only the two forms of *hAChE*, 4EY4 and 4EY7, but it cannot re-dock HupA into the original *hAChE* in complex with HupA form (4EY5) (see [Table S1, Supporting Information](#)), which indicated that force field parameters and the binding free energy equation of BUDE were limited to analyze molecular docking accurately.<sup>16</sup> This led us to use the



**Figure 3.** Design strategy for novel C(2) HupA derivatives targeting AChE.

AutoDock software for docking instead of BUDE, which is capable to re-dock HupA into original *h*AChE of 4EYS. This showed that the pyridone ring of HupA was positioned in the space between Ser125, Gln71, and Trp86 of the catalytic anionic site (CAS) of the crystallized structure of *h*AChE (4EYS) with distances of 4.141, 5.870, and 4.019 Å, respectively (Figure 2).<sup>17</sup> These results suggested that the substitution at C(2) of HupA could enhance binding affinity with AChE. Though there are previous reports on derivatization of HupA for AChE inhibition, including modifications at the exocyclic ethylidene group,<sup>18</sup> the pyridone ring,<sup>19</sup> the primary amine,<sup>9,20</sup> and the C(6) methylene position,<sup>21–24</sup> to the best of our knowledge, C(2) modification has not been investigated. Here, we report (i) the rational design of C(2)-functionalized HupA analogs guided by *in silico* studies (molecular docking and pharmacokinetic properties prediction); (ii) the semi-synthesis of the selected C(2)-functionalized HupA analogs; (iii) *in vitro* inhibitory activity of these novel analogs on electric eel AChE (*ee*AChE) and equine serum BChE (*eq*BChE); and (iv) structure–activity relationship (SAR) analysis of the C(2) HupA analogs described in this paper.

## RESULTS AND DISCUSSION

**In Silico-Guided Rational Drug Design.** The C(2) functionalization of HupA was designed to enhance molecular interactions of the HupA derivatives with AChE. Twenty-eight molecules, including C(2)-functionalized and O- or N-methyl-substituted HupA analogs, were subjected to SwissADME database (<http://www.swissadme.ch/>) to screen for drug-like characteristics and associated pharmacokinetic properties. Among this group, 12 C(2)-functionalized and four O- or N-methyl-substituted HupA analogs met the criteria of Lipinski's rules and blood–brain barrier (BBB) permeability (Figure 3).

Molecular docking studies of these selected HupA derivatives (with C(2) substituents including halogens, small alkyl groups, hydroxyl, amino, nitrile, and small alkoxy groups) were then performed using Autodock software.<sup>25,26</sup> As shown in Table 1, C(2) analogs 5, 6, 8, 9, and 10 yielded lower binding free energies with AChE than that determined for the parent compound 1.

**Physicochemical Properties.** The calculated physicochemical properties of the preselected HupA derivatives, such as the number of H-bond acceptors (HBA), number of H-bond donors (HBD), number of rotatable bonds (RB), topological polar surface area (*t*PSA), and calculated *n*-octanol/water partition coefficient (*c*LogP) were predicted, as shown in Table 2. The results demonstrated that most derivatives fell within the scope of Lipinski's rule of five except parent compound 1 and HupA analogs 7–10 where *c*LogP values were not within the orally available drug range.<sup>27</sup> For blood–brain barrier permeability, the logarithm of the brain to blood concentration ratio (log BB) was calculated by using Clark's model to determine the characteristic of the passages of the HupA derivatives through the BBB.<sup>28</sup> The predicted log BB values of all derivatives were greater than −1, which affirmed the possibility that these derivatives could be developed into CNS drugs.<sup>28</sup>

**Synthesis of HupA Derivatives.** We focused on the use of a range of metal-catalyzed transformations based on a C(2)-halogenated variant of HupA as a synthetic entry to the C(2) analogs that had been identified by *in silico* assessment. To avoid interference by the existing (albeit very hindered) primary amine of HupA, the amino group needed to be protected.<sup>31</sup> Three common protecting groups including *tert*-butyloxycarbonyl (Boc), acetyl (Ac), and triflate (Tf) were chosen as our first trials to search for the suitable protecting groups (see the Supporting Information, Scheme S1).<sup>32</sup> When

**Table 1. Molecular Docking Analysis of Compounds 1–17 against hAChE (4EYS) and hBChE (4XII) Using Autodock Software**

compound	hAChE (4EYS)			hBChE (4XII)		
	estimated free energy of binding (kcal/mol) <sup>a</sup>	estimated inhibition constant, K <sub>i</sub> (nM) <sup>a</sup>	H-bond interaction residues (distance in Å) <sup>b</sup>	estimated free energy of binding (kcal/mol) <sup>a</sup>	estimated inhibition constant, K <sub>i</sub> (nM) <sup>a</sup>	H-bond interaction residues (distance in Å) <sup>b</sup>
<b>HupA 1</b>	−12.17	1.20	Tyr337 (2.90), Tyr133 (2.75, 3.15)	−8.08	1.20 μM	Glu197 (2.50)
<b>2</b>	−12.10	1.34	Tyr133 (2.92)	−9.21	177.89	
<b>3</b>	−10.63	16.24	Tyr133 (2.51), Gly120 (3.15)	−8.87	313.41	Asp70 (2.48), Thr120 (2.36), Tyr332 (2.99)
<b>4</b>	−12.00	1.62	Tyr133 (2.87)	−8.65	453.73	Glu197 (2.77)
<b>5</b>	−12.20	1.13	Tyr133 (2.90, 3.15)	8.33	780.19	Asp70 (2.38), Tyr332 (2.69)
<b>6</b>	−12.31	0.95	Tyr133 (2.78)	−8.92	290.98	
<b>7</b>	−10.25	30.64	Tyr133 (2.92), Tyr337 (2.84)	−8.91	296.05	
<b>8</b>	−12.19	1.17	Trp86 (2.98), Tyr133 (2.87)	−8.65	458.89	Tyr128 (2.43), Glu197 (2.74)
<b>9</b>	−12.47	0.73	Trp86 (2.91), Tyr133 (2.89)	−8.86	321.81	Tyr128 (2.43), Glu197 (2.78)
<b>10</b>	−12.75	0.45	Tyr133 (2.84), Glu202 (2.70)	−9.40	129.68	Glu197 (2.51)
<b>11</b>	−11.30	5.23	Gly120 (2.75), Tyr133 (2.64)	−8.64	468.08	Asp70 (2.36), Tyr (2.68)
<b>12</b>	−11.04	8.13		−8.89	302.29	Asp70 (2.49), Tyr332 (2.67)
<b>13</b>	−8.45	643.06		−8.77	370.76	Glu197 (2.97), His438 (2.77)
<b>14</b>	−12.21	1.11	Glu202 (2.53)	−8.99	258.05	Glu197 (2.65)
<b>15</b>	−8.39	713.34	Ser203 (2.61), His447 (3.22)	−7.29	4.50 μM	Ser198 (3.29), His438 (2.68)
<b>16</b>	−9.11	211.03	Gly120 (2.99)	−7.38	3.88 μM	
<b>17</b>	−7.63	2.56 μM		−7.55	2.91 μM	Ser79 (3.09)
donepezil <sup>c</sup>	−12.42	0.78	Phe295 (2.99)	−9.99	47.44	

<sup>a</sup>Binding free energy and inhibitory constant results obtained from AutoDock 4.2.6 software.<sup>25</sup> <sup>b</sup>Molecular docking visualization and H-bonding measurement of each compound were obtained from UCSF Chimera Molecular graphics, and analyses were performed with UCSF Chimera.<sup>26</sup>

<sup>c</sup>Donepezil, a known selective AChE inhibitor.<sup>29</sup>

HupA was treated with acetyl chloride in the presence of pyridine, the isomerized product **19** was observed based on NMR, possibly due to *in situ* generation of HCl or acetic acid.<sup>33</sup> Isomerization was avoided when HupA was treated with acetic anhydride,<sup>34</sup> and the desired acetyl-protected HupA **18** was isolated in 64% yield. The *N*-Tf- and *N*-Boc-protected variants **20** and **21** were prepared<sup>35,36</sup> and isolated in 38 and 29% yields, respectively, reflecting the hindered nature of this amine moiety. The acetyl-protected variant **18** was the most suitable since the protected HupA could be prepared in moderate yield and the acetyl group is removable under basic conditions, thus mitigating any risk of acid-promoted alkene isomerization.<sup>37</sup> Halogenation of *N*-Ac HupA **18** was carried out under standard conditions<sup>38,39</sup> to give the corresponding 2-bromo and 2-iodo derivatives **22** and **23** in good yields; however, we were then unable to remove the *N*-acetamide residue (see the Supporting Information, Scheme S1).

Given the reactivity associated with pyridone toward electrophilic substitution (which would favor reaction at C(2))<sup>40</sup> coupled with the hindered nature of the primary amino moiety, we explored an alternative approach, avoiding *N*-protection, as shown in Scheme 1. Unprotected HupA **1** underwent smooth and efficient electrophilic halogenation to give 2-bromohuperzine A (**2**) and 2-iodohuperzine A (**3**),<sup>38,39</sup> which then became attractive building blocks for further functionalization *via* various types of cross-coupling reactions.

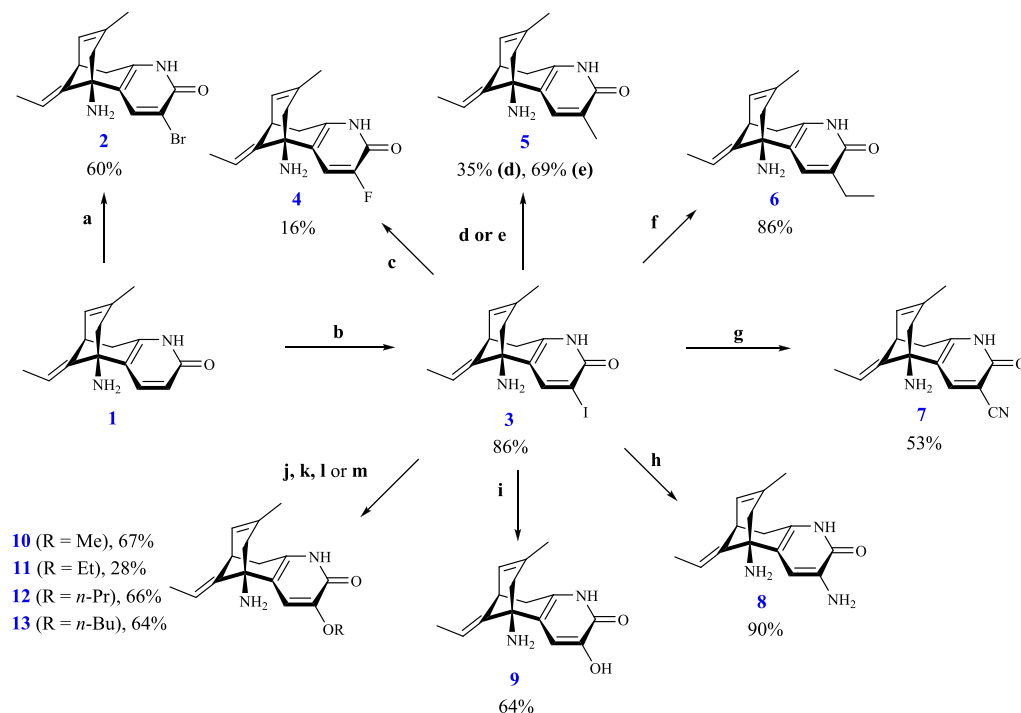
2-Fluorohuperzine A (**4**) was then prepared from iodide **3** reacting with 1-chloromethyl-4-fluoro-1,4-diazoniabicyclo[2.2.2]octane bis(tetrafluoroborate) using Pd(dppf)Cl<sub>2</sub> as a catalyst in THF under reflux for 96 h.<sup>41</sup> 2-Alkyl HupA derivatives were prepared using Kumada or Negishi cross-coupling reactions.<sup>42,43</sup> The reaction of iodide **3** using Negishi's method was found to be more effective, affording the methylated and ethylated analogs **5** and **6** in 69 and 86% yields, respectively. The bromo analog **2** was, however, inert under these conditions. 2-Cyanohuperzine A (**7**) was prepared in 53% yield from **3** by the *L*-proline-promoted Rosenmund–von Braun reaction at 120 °C.<sup>44</sup> The copper-catalyzed heteroarene amination of **3** gave 2-aminohuperzine A (**8**)<sup>44</sup> in 90% yield. Since the corresponding 2-hydroxy was observed as a byproduct,<sup>45</sup> these conditions were adapted to provide 2-hydroxyhuperzine A (**9**) in 64% yield using water as a hydroxide source, instead of aqueous ammonia solution. With the successful and simple synthetic methods for **8** and **9**, the 2-alkoxy-HupA derivatives (**10–13**) were prepared by using an alcohol as the nucleophilic component to provide **10–13** in fair to good yields.

In addition to the C(2) functionalization of HupA, the modification of the pyridone ring of HupA into *O*-alkyl pyridine derivatives was performed to extend the structure–activity relationship (SAR) to *O*- or *N*-methyl-substituted HupA and *O*- or *N*-unsubstituted HupA, as shown in Scheme

Table 2. Physicochemical Properties of Compounds 1–17

compound	MW <sup>a</sup>	HBA <sup>b</sup>	HBD <sup>b</sup>	RB <sup>b</sup>	tPSA <sup>b</sup>	cLogP <sup>b</sup>	log BB <sup>c</sup>
1	242.32	2	2	0	58.88	1.88	-0.45
2	321.22	2	2	0	58.88	2.53	-0.35
3	368.22	2	2	0	58.88	2.56	-0.34
4	260.31	3	2	0	58.88	2.26	-0.39
5	256.35	2	2	0	58.88	2.22	-0.39
6	270.38	2	2	1	58.88	2.55	-0.34
7	267.33	3	2	0	82.67	1.71	-0.82
8	257.34	2	3	0	84.90	1.40	-0.90
9	258.32	3	3	0	79.11	1.58	-0.79
10	272.35	3	2	1	68.11	1.88	-0.58
11	286.38	3	2	2	68.11	2.21	-0.53
12	300.40	3	2	3	68.11	2.57	-0.48
13	314.43	3	2	4	68.11	2.91	-0.43
14	256.35	3	1	1	48.14	2.50	-0.19
15	284.40	3	0	2	25.36	3.09	0.23
16	284.40	2	0	1	25.36	3.09	0.23
17	270.37	2	1	1	36.10	2.92	0.05
donepezil <sup>d</sup>	381.51	4	0	6	38.77	3.85	0.15
required parameters <sup>e</sup>	<500	<10	<5	<10	<90	2–5	>–1.00

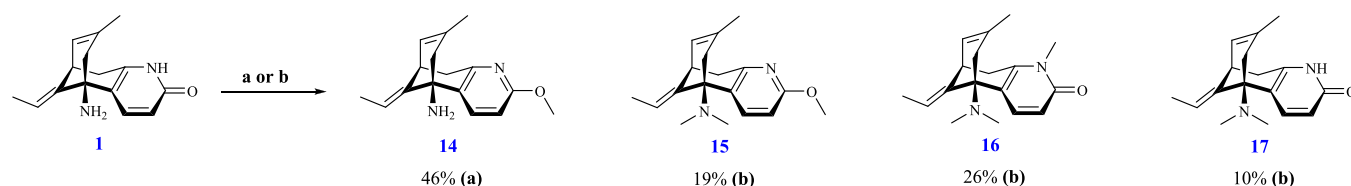
<sup>a</sup>Calculated using ChemBioDraw Ultra16.0. MW: molecular weight. <sup>b</sup>Calculated using SwissADME (<http://www.swissadme.ch/>).<sup>30</sup> HBA: number of hydrogen acceptors; HBD: number of hydrogen donors; RB: number of rotatable bonds; tPSA: total polar surface area; cLog P: log octanol/water partition coefficient. <sup>c</sup>log BB =  $-0.0148 \times tPSA + 0.152 \times cLogP + 0.139$ .<sup>28</sup> <sup>d</sup>Donepezil, a known selective AChE inhibitor.<sup>29</sup> <sup>e</sup>Required parameters necessary to fulfill appropriate physicochemical properties as judged appropriately according to Lipinski's rules and those important for BBB permeation.<sup>27</sup>

Scheme 1. Synthesis of C(2)-Functionalized HupA Derivatives 2–13<sup>a</sup>

<sup>a</sup>Reaction conditions: (a) NBS, DCM, RT, 24 h; (b) NIS, DCM, RT, 48 h; (c) 1-chloromethyl-4-fluoro-1,4-diazoniabicyclo[2.2.2]octane bis(tetrafluoroborate), Pd(dppf)Cl<sub>2</sub>, THF, reflux, 96 h; (d) CH<sub>3</sub>MgBr, Pd(dppf)Cl<sub>2</sub>, THF, reflux, 72 h; (e) Zn(CH<sub>3</sub>)<sub>2</sub>, Pd(dppf)Cl<sub>2</sub>, THF, reflux, 72 h; (f) Zn(CH<sub>2</sub>CH<sub>3</sub>)<sub>2</sub>, Pd(dppf)Cl<sub>2</sub>, THF, reflux, 72 h; (g) CuCN, K<sub>2</sub>CO<sub>3</sub>, DMF, 120 °C, 72 h; (h) NH<sub>3</sub> (aq.), CuI, K<sub>2</sub>CO<sub>3</sub>, 140 °C, 72 h; (i) H<sub>2</sub>O, CuI, K<sub>2</sub>CO<sub>3</sub>, 130 °C, 72 h; (j) MeOH, CuI, K<sub>2</sub>CO<sub>3</sub>, 140 °C, 72 h; (k) EtOH, CuI, K<sub>2</sub>CO<sub>3</sub>, 140 °C, 72 h; (l) *n*-PrOH, CuI, K<sub>2</sub>CO<sub>3</sub>, 140 °C, 72 h; (m) *n*-BuOH, CuI, K<sub>2</sub>CO<sub>3</sub>, 140 °C, 72 h.

2. By following a protocol reported by White and co-workers,<sup>46</sup> *O*-methyl-substituted HupA (14) was obtained in 46% yield by treatment of 1 with an excess of iodomethane and Ag<sub>2</sub>CO<sub>3</sub> for

45 h at room temperature. When the reaction time was increased to 72 h, a mixture of *O*- or *N*-methyl-substituted HupA including *N,N,O*-trimethyl huperzine A (15, 19%),

Scheme 2. Synthesis of HupA Derivatives 14–17<sup>a</sup>

<sup>a</sup>Reaction conditions: (a) CH<sub>3</sub>I, Ag<sub>2</sub>CO<sub>3</sub>, DCM, RT, 45 h; (b) CH<sub>3</sub>I, Ag<sub>2</sub>CO<sub>3</sub>, DCM, RT, 72 h.

Table 3. *In Vitro* Inhibitory Activity of Compounds 1–17 toward Cholinesterases

compound	R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	R <sup>4</sup>	cholinesterase IC <sub>50</sub> (μM) <sup>a</sup>		SI <sup>d</sup>
					<i>ee</i> AChE <sup>b</sup>	<i>eq</i> BChE <sup>c</sup>	
1	H	H	H	H	0.03 ± 0.00	68.78 ± 03.15	2,273
2	Br	H	H	H	2.56 ± 0.17	72.29 ± 04.57	28
3	I	H	H	H	14.12 ± 0.84	325.22 ± 38.63	23
4	F	H	H	H	1.23 ± 0.01	63.998 ± 03.63	52
5	Me	H	H	H	0.35 ± 0.02	486.03 ± 29.71	1,388
6	Et	H	H	H	0.57 ± 0.09	60.39 ± 02.54	105
7	CN	H	H	H	33.88 ± 1.95	1,050.88 ± 498.89	31
8	NH <sub>2</sub>	H	H	H	0.32 ± 0.01	524.64 ± 41.56	1,634
9	OH	H	H	H	0.53 ± 0.09	154.76 ± 04.14	293
10	OMe	H	H	H	0.16 ± 0.02	599.15 ± 49.76	3,633
11	OEt	H	H	H	0.22 ± 0.04	253.02 ± 12.24	1,154
12	O <sup>n</sup> Pr	H	H	H	10.19 ± 0.50	87.27 ± 01.37	9
13	O <sup>n</sup> Bu	H	H	H	109.65 ± 9.59	16.91 ± 01.23	0.2
14			H	H	3.67 ± 0.28	903.66 ± 88.20	246
15			Me	Me	n.i.	1,348.75 ± 62.31	
16		Me	Me	Me	n.i.	258.70 ± 10.81	
17			Me	Me	0.61 ± 0.02	223.57 ± 47.78	366
donepezil <sup>e</sup>					0.23 ± 0.05	18.00 ± 00.79	79

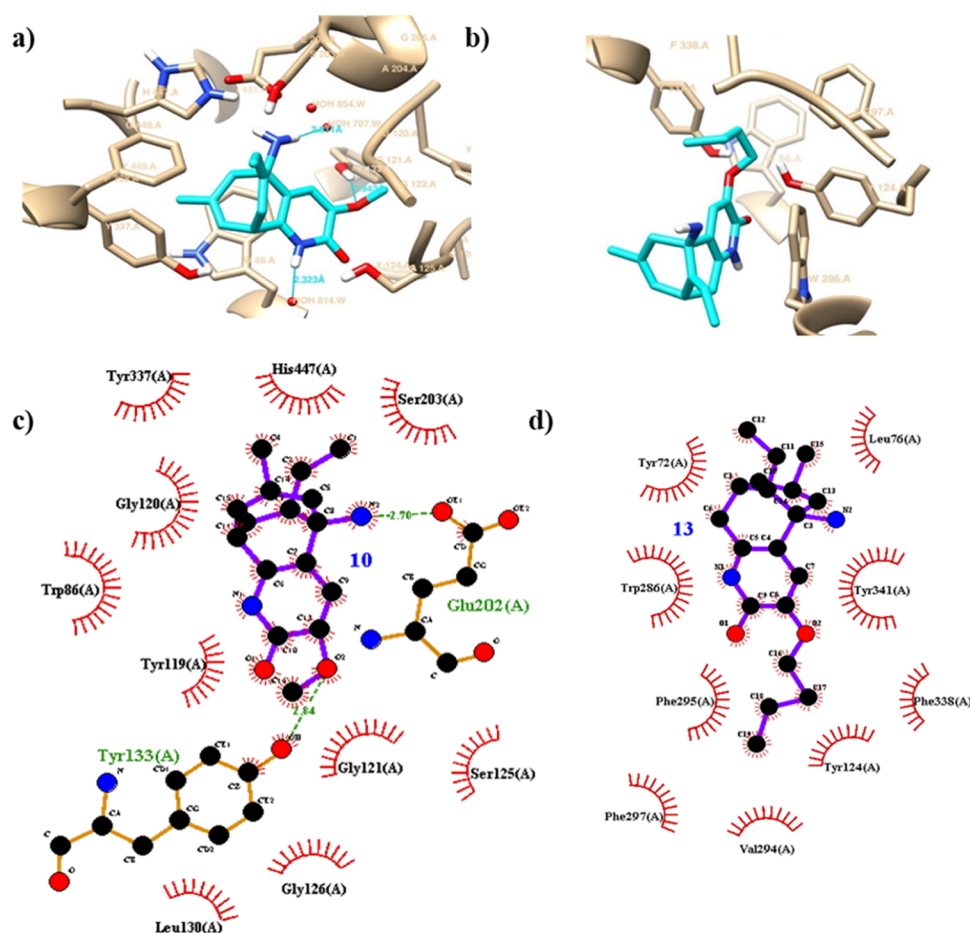
<sup>a</sup>Mean IC<sub>50</sub> (μM) ± SEM, *n* = 3; n.i. = no inhibition. <sup>b</sup>AChE (EC 3.1.1.7) from electric eel. <sup>c</sup>BChE (EC 3.1.1.8) from horse serum. <sup>d</sup>Selectivity index for AChE is defined as IC<sub>50</sub> (BChE)/IC<sub>50</sub> (AChE). <sup>e</sup>Donepezil, a known selective AChE inhibitor used as a positive control.<sup>29</sup>

*N,N,N*-trimethyl huperzine A (**16**, 26%), and *N,N*-dimethyl huperzine A (**17**, 10%) was isolated.

***In Vitro eeAChE and eqBChE Inhibition Assays.*** AChE is the esterase responsible for the regulation of cholinergic transmission *via* hydrolysis of Ach, which is a primary neurotransmitter of sympathetic and parasympathetic ganglionic neurons.<sup>8</sup> Inhibitors of AChE can alleviate the symptoms of ACh decline by increasing cerebral cholinergic transmission at the synaptic cleft<sup>4</sup> and three AChE inhibitors, donepezil, rivastigmine, and galantamine, are currently approved for the treatment of AD.<sup>47</sup> While rivastigmine is a reversible cholinesterase inhibitor that targets both AChE and BChE,<sup>29,48</sup> donepezil and galantamine display better selectivity for AChE.

The *in vitro* activities of the HupA analogs 2–17 prepared to inhibit *ee*AChE and *eq*BChE were assessed using Ellman's method,<sup>49</sup> using donepezil as the reference compound. All compounds were screened at a concentration of 10 μM, and IC<sub>50</sub> values were determined where inhibition was observed. The results for screening against AChE and BChE are shown in Table 3. Among C(2)-functionalized HupA derivatives, compounds 10 and 11 displayed the best *ee*AChE inhibitory

activity with IC<sub>50</sub> values of 0.16 and 0.22 μM, respectively, comparable to that of donepezil (IC<sub>50</sub> = 0.23 μM). Although the enzyme inhibitory results did not track exactly the calculated inhibition constants reported in Table 1, all derivatives tested were less potent than the parent compound HupA 1 (IC<sub>50</sub> = 0.03 μM). This observation is in accordance with many related studies of the AChE and/or BChE inhibitory activity of HupA derivatives.<sup>50</sup> Most of HupA analogs with substitutions at different positions on the skeleton were inactive or less active as an AChE inhibitor than HupA itself.<sup>50</sup> Moreover, while some analogs did show improved activities, this was also linked to a decrease in selectivity. For example, Kozikowski and co-workers<sup>22</sup> reported that introduction of small substituents, such as methyl or ethyl groups, at C(6) of HupA increased the inhibitory potency for AChE (IC<sub>50</sub> ranging from 0.003–2.04 μM toward FBS AChE), compared to the parent compound (IC<sub>50</sub> = 0.024 μM), but they also saw a reduction in selectivity in terms of the BChE/AChE inhibitory activity ratio.<sup>22</sup> Since 2-methoxy-HupA 10 displayed both a comparable level of activity to that of donepezil and better selectivity (selectivity index = 3633) to inhibit *ee*AChE over *eq*BChE than the HupA 1 and donepezil,



**Figure 4.** (a, b) Molecular docking and (c, d) binding mode analysis of compounds **10** and **13** toward AChE (4EY5).

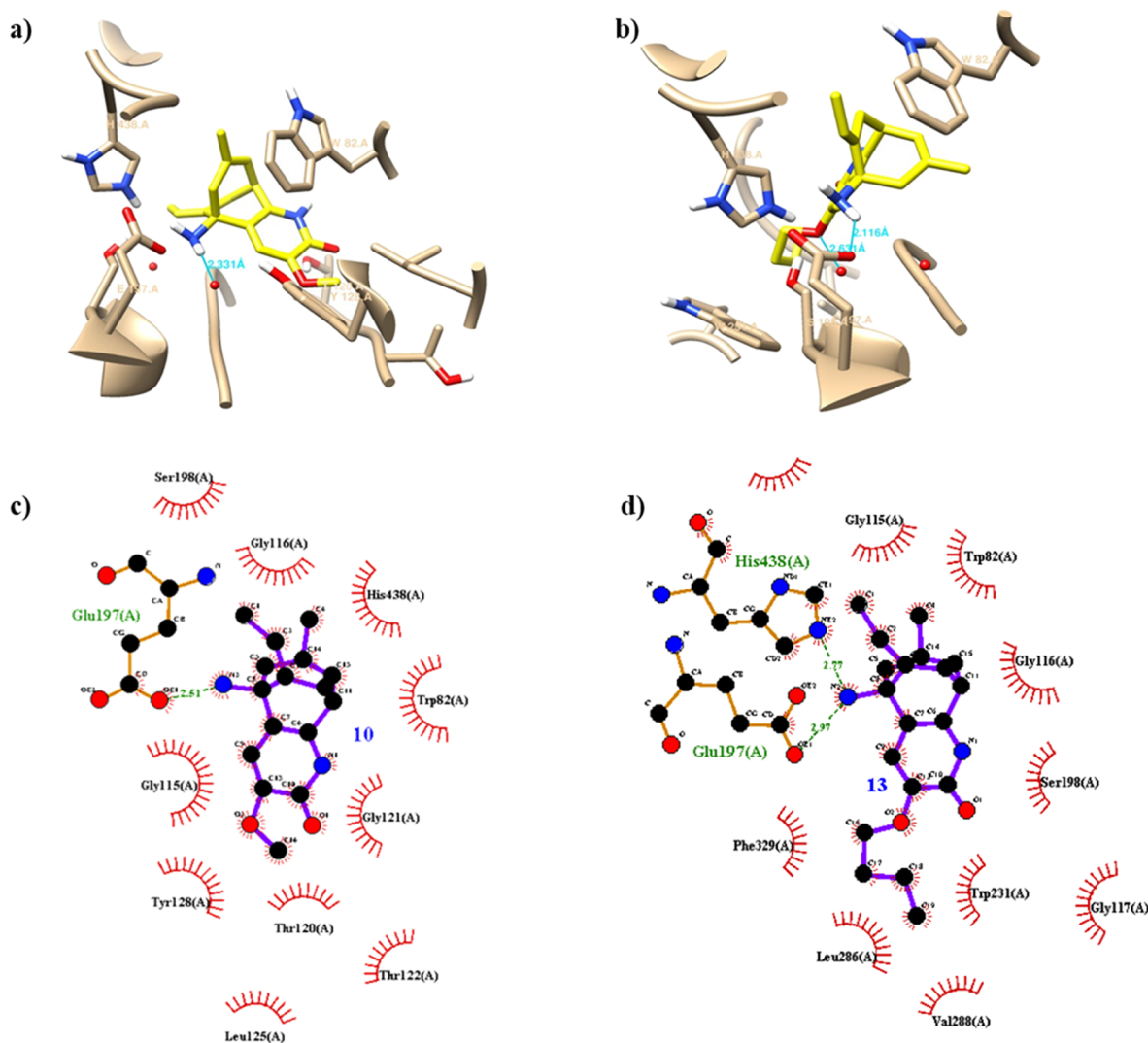
this is a variant that could be assessed more fully for its potential for AD treatment.

Regarding the predicted physicochemical properties of HupA derivatives, as shown in Table 2, compound **10** has properties that fall within the range of the “CNS drug” compound. We observed the high log BB ( $>-1.0$ ) of compound **10** that has small size and is less polar (lower number of hydrogen acceptors, lower number of hydrogen donors, and lower *t*PSA value) as parent compound **1**, suggesting that this compound could pass the BBB to alleviate the ACh level at CNS.

**Structure–Activity Relationship Analysis.** The relationship between the structures of C(2)-functionalized HupA derivatives and cholinesterase  $IC_{50}$  values were evaluated. Introduction of halogen substituents (compounds 2–4) showed a decrease in *ee*AChE inhibitory activity. Increasing atomic radius sizes of halogen atoms also resulted in decreasing *ee*AChE inhibitory activity. For the linear alkyl side chains,  $IC_{50}$  values against *ee*AChE were elevated corresponding to the carbon numbers; from HupA **1** ( $0.03 \pm 0.00 \mu\text{M}$ ) to methyl HupA **5** ( $0.35 \pm 0.02 \mu\text{M}$ ) and ethyl HupA **6** ( $0.57 \pm 0.09 \mu\text{M}$ ). Likewise, 2-methoxy-Hup A (**10**) was the most potent *ee*AChE inhibitor, compared to the other alkoxy derivatives **11–13** assessed, while conversely, the *n*-butoxy variant **13** preferably inhibited *eq*BChE. These observations can be explained by the bulk of the substituent at the C(2) position, preventing entry of the molecules into the AChE active site. The molecular docking and binding mode analysis of **10** and **13** confirmed the steric influence of alkoxy side chains at the C(2) position (Figure 4). The methoxy group of **10** positioned

in the space between Gln69, Trp84, and Ser122 of AChE by the formation of hydrogen bonding between the 2-methoxy and hydroxyl oxygen of Tyr133 of AChE. This alignment fitted the hydrophobic region in CAS of AChE, resulting in the stronger binding to the enzymatic active site. The steric hindrance associated with the large alkyl side chain in compound **13** disrupted the binding affinity to the active site of AChE, giving the least favorable binding free energy (estimated binding free energy,  $-8.45 \text{ kcal/mol}$ ). Similarly, the binding mode analysis of compounds **10** and **13** within the BChE active site was also conducted, as shown in Figure 5. Both compounds occupy the space between Trp82, Tyr128, Glu167, and His438 of BChE with the same alignment as the parent compound **1**. The primary amine in compounds **10** and **13** interacted directly with carboxylate oxygen of Glu197 by H-bonding, while hydrophobic interactions were formed between the bicyclic moiety of the ligand and the indole ring of Trp82 in the same manner. On the other hand, the butoxy derivative **13** situated in the space between Trp231, Leu286, Val288, and Phe329 of BChE. The primary amine of **13** consequently interacted with the imidazole ring of His438 of BChE by H-bonding, corresponding to the lowest *in vitro*  $IC_{50}$  value for *eq*BChE activity inhibition.

The reliability of *in silico*-guided analysis was determined by correlation of estimated  $K_i$  (from docking analysis) and experimentally determined  $K_i$  (from the *in vitro* AChE inhibitory assay) values. According to the known inhibition mode of HupA, we deduce that C(2)-functionalized HupA derivatives 2–13 are competitive inhibitors. The experimental



**Figure 5.** (a, b) Molecular docking and (c, d) binding mode analysis of compounds **10** and **13** toward BChE (4XII).

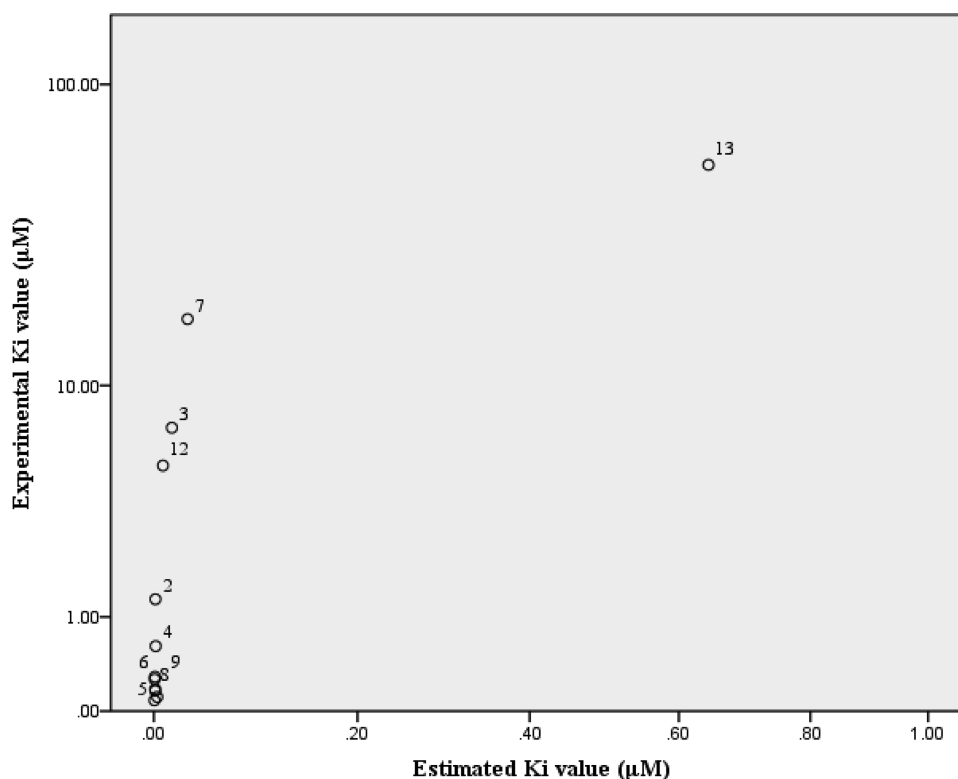
$K_i$  values of all derivatives were calculated from *in vitro*  $IC_{50}$  values using the equations proposed by Cer and co-workers ( $K_i = IC_{50}/2$ ).<sup>31</sup> Pearson's and Spearman's correlation coefficients for regression between the  $K_i$  values were also analyzed (Figure 6). The results demonstrated that the relationship between estimated  $K_i$  and experimentally determined  $K_i$  has a significant positive trend where both correlation coefficients are greater than zero (Pearson's and Spearman's coefficients of 0.96 and 0.78, respectively). The result suggested that *in silico*-guided analysis could be utilized as a reliable tool for rational drug design.

In addition to C(2)-functionalized derivatives, the structure–activity relationship of the *O*- or *N*-methyl-substituted HupA analogs was also analyzed. All *O*- or *N*-methyl-substituted HupA derivatives **14**–**17** exhibited less potent inhibitory activity on *ee*AChE than HupA **1**. The *N*- or *O*-methylated HupA derivatives, such as *N,N,O*-trimethyl HupA (**15**) and *N,N,N*-trimethyl HupA (**16**), showed no inhibition of *ee*AChE, corresponding to the *in silico* analysis that had indicated that the heteroatoms of both the pyridone ring and primary amine of HupA were necessary for binding to the active site of AChE. *N,N*-Dimethyl HupA (**17**) showed greater *ee*AChE inhibitory activity than the *O*-methyl HupA (**14**), suggesting that interactions involving the pyridone ring of

HupA were more crucial than the amino group for AChE inhibition. Methyl substitution at the nitrogen pyridone ring of HupA has been evaluated for the AChE inhibitory activity.<sup>18</sup> This compound showed low potency for brain AChE inhibitory activity, similar to the activity that we observed for compound **16**. Moreover, the transformation of the pyridone ring from the pyridone ring of HupA as catechol analogs was also reported with inactivity or less activity than HupA in AChE.<sup>24</sup>

To evaluate the cytotoxicity of the HupA derivatives reported here and donepezil, an MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay was performed. Each compound was tested at two concentrations, 10 and 100  $\mu$ M, against human lung fibroblast cells (IMR90). As demonstrated in Table 4, at 10  $\mu$ M concentration, all compounds failed to affect the cell proliferation. Among them (and at 100  $\mu$ M), only **6**, **15**, and donepezil showed some cytotoxicity while compound **6** was still significantly less toxic than donepezil. Interestingly, we did not observe any cell toxicity for ligand **10**, which is the most promising selective inhibitor that we have identified.





**Figure 6.** Correlation of the estimated  $K_i$  value according to the docking program and calculated  $K_i$  according to *in vitro* results. Correlation is significant at the  $p < 0.001$  level (two-tailed).

**Table 4.** *In Vitro* Cytotoxicity of HupA Derivatives and Donepezil against IMR90 Cells<sup>a</sup>

compound	%cytotoxicity <sup>b</sup>		compound	%cytotoxicity <sup>b</sup>	
	10 $\mu$ M	100 $\mu$ M		10 $\mu$ M	100 $\mu$ M
1	n.i.	n.i.	10	n.i.	n.i.
2	n.i.	n.i.	11	n.i.	n.i.
3	n.i.	n.i.	12	n.i.	n.i.
4	n.i.	n.i.	13	n.i.	n.i.
5	n.i.	n.i.	14	n.i.	n.i.
6	n.i.	2.2 $\pm$ 2.4 <sup>c</sup>	15	n.i.	5.5 $\pm$ 9.7
7	n.i.	n.i.	16	n.i.	n.i.
8	n.i.	n.i.	17	n.i.	n.i.
9	n.i.	n.i.	donepezil	n.i.	29.0 $\pm$ 12.5

<sup>a</sup>IMR90 cells were treated with each compound at the indicated concentrations for 24 h. Cell viability was determined by the MTT assay. <sup>b</sup>The values are shown as mean  $\pm$  SEM,  $n = 3$ . n.i. = no inhibition. <sup>c</sup>Significantly different from donepezil (100  $\mu$ M) with  $p < 0.05$ .

## CONCLUSIONS

In this paper, we report the semi-synthesis of a set of novel C(2)-functionalized HupA derivatives that were designed using *in silico* binding affinity to AChE and predicted the pharmacokinetic properties. Among the variants synthesized, 2-methoxy-HupA **10** was found to be the most potent *ee*AChE inhibitor with improved selectivity over *eq*BChE, compared to HupA ( $\sim 2$  times) and donepezil ( $\sim 46$  times). In addition, using an MTT assay, ligand **10** was significantly less cytotoxic than donepezil. These results suggested the potential of ligand **10** to be further developed as an AD treatment with less peripheral side effects. The structure–activity relationship of the *O*- or *N*-methyl-substituted HupA compounds **14**–**17** was

also studied. The results revealed that the nitrogen atom of the pyridone ring, rather than the primary amine of HupA, was crucial for AChE binding. The detailed structure–activity relationship analysis of HupA derivatives reported here should be useful for the future development of anti-AD drugs.

## EXPERIMENTAL SECTION

**Computational Analysis.** *Preparation of the Structures of HupA Derivatives.* Structures of HupA and its analogs were constructed in ChemDraw Professional 16.0 followed by three-dimensional (3D) structure transformation using Chem3D Professional 10.0. All analogs were then energetically minimized by Chem3D Professional 10.0 by using the MM2 force field to avoid any steric clashes of the freely rotatable bond.

*Molecular Docking of HupA Analogs into AChE.* The binding free energy and inhibitory constant  $K_i$  of HupA, HupA analogs, and donepezil (as a reference compound with AChE inhibition) were docked and analyzed by using AutoDock 4.2.6 software. The crystal structures of human AChE (PDB entry: 4EYS) and BChE (PDB entry: 4XII) were prepared by removing all water molecules, any solvent, and the ligand. Each energy-minimized HupA analogs were submitted with default parameters of docking procedures. The binding site sphere for HupA derivatives interaction was defined around the catalytic site according to previous studies (Tyr72, Asp74, Trp86, Gly121, Gly122, Glu202, Ser203, Ala204, Trp236, Trp286, Phe295, Phe297, Glu334, Tyr337, Phe338, and His447 for the AChE active site and Trp82, Trp231, Phe329, and Tyr332 for the BChE active site). The Ser124 and Gln71 residues were also included to determine the free pocket space of AChE for the C(2) functional group of HupA derivatives. The molecular docking protocol was obtained from the active site of the

AChE and BChE with a molecular grid at 0.375 Å grid spacing. The grids were located at  $x = -6.750$ ,  $y = -6.250$ , and  $z = 3.389$  Å for AChE and  $x = 4.302$ ,  $y = -7.649$ , and  $z = -14.515$  Å for BChE. Docking results of all HupA analogs with AChE and BChE were evaluated as the best binding free energy (BE, kcal/mol) and inhibitory constant  $K_i$  from all clusters of each conformational structure. Virtual analysis of the best result of each analog was viewed and analyzed by using UCSF Chimera.<sup>26</sup>

**Computational Pharmacokinetic Analysis.** The SwissADME is a free web tool to compute the physicochemical properties of a small molecule to evaluate lead candidates of HupA analogs (<http://www.swissadme.ch/index.php>).<sup>30</sup> All analogs were submitted in the SMILES format to calculate the pharmacokinetic properties of HupA analog candidates. The physicochemical properties of SwissADME results include molecular weight (MW), number of heavy atoms, number of the rotatable bonds, number of H-bond acceptors (HA), number of H-bond donors, polar surface area (PSA), and lipophilicity were obtained.

**Semi-synthesis of HupA Analogs. General Chemistry.** The HupA (**1**) starting material was isolated from clubmosses *H. squarrosa* (G. Forst.) Trevis., *H. carinata* (Desv. ex. Poir.) Trevis., *H. phlegmaria* (L.), and *P. nummulariifolius* (Blume) Chambers (Lycopodiaceae),<sup>13–15</sup> and used in the semi-synthesis of *N*-protection of HupA derivatives (Scheme 2 and Scheme S1). Commercial HupA (99% purity) was purchased from Changsha Zhongren Biotechnology (Changsha City, Hunan, China) and used in the semi-synthesis of C(2)-functionalized HupA derivatives, as shown in Scheme 1. All reagents and solvents were obtained from commercial suppliers and used without further purification. The reactions were performed based on previously published procedures and monitored by thin-layer chromatography (TLC) on silica gel pre-coated aluminum plates (70–230 mesh). The TLC spots were visualized by UV light at 254 and 365 nm. The purification of all desired products was carried out by using silica gel column chromatography (70–230 mesh of SiliCycle silica gel), which provided isolated yield. <sup>1</sup>H and <sup>13</sup>C NMR spectra were collected on a Bruker AVANCE at 300 and 75 MHz, respectively. Chemical shifts ( $\delta$ ) were reported in parts-per-million (ppm) relative to residual solvent signals. The 1D spectra was measured in CDCl<sub>3</sub>, which were referenced to 7.26 ppm for <sup>1</sup>H NMR and 77 ppm for <sup>13</sup>C NMR. High-resolution mass spectra were obtained using electron spray ionization (ESI) on a Thermo Scientific QTOF instrument.

**Formation of Compound 2 by Bromination of Huperzine A (1).** HupA (**1**, 0.21 mmol, 50 mg) was treated with *N*-bromosuccinimide (NBS, 0.62 mmol, 110 mg) in CH<sub>2</sub>Cl<sub>2</sub> (1.0 mL) at room temperature for 24 h. The reaction mixture was quenched with H<sub>2</sub>O (5 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (5 mL). The combined organic layers were washed with sat. NaCl (5 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and concentrated under reduced pressure. The crude product was purified by flash column chromatography (4–7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-bromohuperzine A (**2**, 40 mg, 60%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-3-bromo-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (2).** Yellowish solid; m.p. 199–200 °C; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –135.2° (*c* 2.5, CH<sub>3</sub>OH);  $R_f$  = 0.40 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2927, 1638, 1610, 1549, 1457, 600 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_H$  8.30 (s, 1H), 5.49 (q, *J* = 6.6 Hz, 1H),

5.43 (d, *J* = 6.0 Hz, 1H), 3.60–3.66 (m, 1H), 2.88 (dd, *J* = 16.5, 6.0 Hz, 1H), 2.76 (dd, *J* = 16.5, 3.0 Hz, 1H), 2.13 (d, *J* = 6.0 Hz, 2H), 1.68 (d, *J* = 6.6 Hz, 3H), 1.56 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_C$  161.4, 143.3, 142.3, 142.1, 134.1, 124.3, 124.0, 111.8, 111.74, 54.39, 49.24, 35.1, 32.8, 22.6, 12.4; (+)-HRMS (ESI) *m/z* calcd for C<sub>15</sub>H<sub>18</sub><sup>79</sup>BrN<sub>2</sub>O [M + H]<sup>+</sup>, 321.0597; found 321.0585.

**Formation of Compound 3 by Iodination of Huperzine A (1).** HupA (**1**, 0.41 mmol, 100 mg) was treated with *N*-iodosuccinimide (NIS, 0.62 mmol, 139 mg) in CH<sub>2</sub>Cl<sub>2</sub> (2.5 mL) at room temperature for 72 h. The reaction mixture was quenched with H<sub>2</sub>O (10 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and concentrated under reduced pressure. The crude product was purified by flash column chromatography (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-iodohuperzine A (**3**, 103 mg, 68%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-3-iodo-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (3).** White-yellowish solid; m.p. 250–251 °C; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –151.0° (*c* 4.0, CH<sub>3</sub>OH);  $R_f$  = 0.46 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2924, 1630, 1606, 1541, 1449, 589 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_H$  8.49 (s, 1H), 5.46 (q, *J* = 6.6 Hz, 1H), 5.41 (d, *J* = 6.0 Hz, 1H), 3.59–3.63 (m, 1H), 2.85 (dd, *J* = 18.0, 6.0 Hz, 1H), 2.73 (dd, *J* = 18, 3.0 Hz, 1H), 2.11 (s, 2H), 1.65 (d, *J* = 6.6 Hz, 3H), 1.53 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_C$  162.4, 149.1, 144.5, 142.1, 134.1, 124.6, 124.4, 111.7, 87.3, 54.3, 49.3, 35.1, 32.8, 22.7, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>15</sub>H<sub>18</sub>I<sub>2</sub>N<sub>2</sub>O [M + H]<sup>+</sup>, 369.0458; found 369.0451.

**Formation of Compound 4 by Fluorination of 2-Iodohuperzine A (3).** To a solution of 2-iodohuperzine A (**3**, 0.14 mmol, 50 mg) in THF (1.0 mL) were added bis(triphenylphosphine)palladium dichloride (20 mg, 4 mol %) and 1-chloromethyl-4-fluoro-1,4-diazoniabicyclo[2.2.2]octane bis(tetrafluoroborate) (0.68 mmol, 241 mg). The mixture was heated at reflux temperature for 96 h under an Ar atmosphere. After cooling to room temperature, the reaction mixture was quenched with H<sub>2</sub>O (10 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and concentrated under reduced pressure. The crude product was purified by flash column chromatography (5% v/v MeOH in ethyl acetate) to afford 2-fluorohuperzine A (**4**, 6 mg, 16%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-3-fluoro-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (4).** Yellowish semisolid; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –48.0° (*c* 1.0, CH<sub>3</sub>OH);  $R_f$  = 0.2 (100% ethyl acetate); IR (neat)  $\nu$  2920, 1662, 1619, 1437, 1305 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_H$  7.74 (d, *J* = 6.0 Hz, 1H), 5.49 (q, *J* = 6.0 Hz, 1H), 5.41 (d, *J* = 3.0 Hz, 1H), 3.60–3.64 (m, 1H), 2.87 (d, *J* = 18.0 Hz, 1H), 2.70 (d, *J* = 18.0 Hz, 1H), 2.13 (s, 1H), 2.11 (s, 1H), 1.69 (d, *J* = 9.0 Hz, 3H), 1.56 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_C$  158.2, 138.1, 134.26, 124.3, 121.9, 121.7, 111.8, 77.4, 54.5, 49.1, 34.8, 33.0, 29.8, 22.7, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>15</sub>H<sub>18</sub>FN<sub>2</sub>O [M + H]<sup>+</sup>, 261.1398; found 261.1399.

**Formation of Compound 5 by Methylation of 2-Iodohuperzine A (3) Using the Negishi Cross-Coupling Reaction.** To a solution of 2-iodohuperzine A (**3**, 0.27 mmol, 100 mg) in THF (1.0 mL) were added bis(triphenylphosphine)palladium dichloride (22 mg, 10 mol %) and dimethylzinc (0.81 mmol, 0.8 mL of 1 M dimethylzinc

in toluene solution). The resulting yellow solution was heated at reflux temperature for 72 h under an Ar atmosphere. After cooling to room temperature, the reaction mixture was quenched with methanol (1.0 mL) and *tert*-butyl methyl ether (10 mL). The resulting mixture was washed three times with water (10 mL) and sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated under reduced pressure. The crude product was purified by flash column chromatography (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-methylhuperzine A (**5**, 46 mg, 67%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-3,7-dimethyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (5).** Brownish solid; m.p. 83–85 °C;  $[\alpha]_{\text{D}}^{26} -150.0^{\circ}$  (*c* 3.8, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.26 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2918, 1642, 1618, 1572, 1263 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.71 (s, 1H), 5.47 (q, *J* = 9.0 Hz, 1H), 5.41 (s, 1H), 3.55–3.65 (m, 1H), 2.87 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.56 (d, *J* = 15.0, 1H), 2.14 (s, 2H), 2.12 (s, 3H), 1.67 (d, *J* = 6.0 Hz, 3H), 1.54 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  165.3, 142.9, 140.0, 137.4, 134.2, 125.8, 124.4, 122.1, 110.9, 54.4, 49.2, 35.0, 33.1, 22.7, 16.5, 12.4; (+)-HRMS (ESI) *m/z* calcd for C<sub>16</sub>H<sub>21</sub>N<sub>3</sub>O [M + H]<sup>+</sup>, 257.1648; found 257.1647.

**Formation of Compound 6 by Ethylation of 2-Iodohuperzine A (3) Using the Negishi Cross-Coupling Reaction.** To a solution of 2-iodohuperzine A (**3**, 0.27 mmol, 100 mg) in THF (1.0 mL) were added bis-(triphenylphosphine)palladium dichloride (22 mg, 10 mol %) and diethylzinc (0.81 mmol, 0.8 mL of 1 M diethylzinc in toluene solution). The resulting yellow solution was heated at reflux temperature for 72 h under an Ar atmosphere. After cooling to room temperature, the reaction mixture was quenched with methanol (1.0 mL) and *tert*-butyl methyl ether (10 mL). The resulting mixture was washed three times with water and sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated under reduced pressure. The crude product was purified by flash column chromatography (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-ethylhuperzine A (**6**, 29 mg, 39%).

**(5*R*,9*R*,*E*)-5-Amino-3-ethyl-11-ethylidene-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (6).** Brownish solid; m.p. 243–244 °C;  $[\alpha]_{\text{D}}^{26} -173.0^{\circ}$  (*c* 2.0, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.31 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2972, 1643, 1620, 1568, 1264 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.70 (s, 1H), 5.47 (q, *J* = 6.0 Hz, 1H), 5.39 (d, *J* = 3.0 Hz, 1H), 3.55–3.65 (m, 1H), 2.85 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.66 (d, *J* = 18.0 Hz, 1H), 2.52 (q, *J* = 6.0 Hz, 2H), 2.19 (s, 1H), 2.10 (s, 1H), 1.67 (d, *J* = 6.0 Hz, 3H), 1.54 (s, 3H), 1.18 (t, *J* = 6.0 Hz, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  164.7, 142.6, 139.8, 135.6, 134.2, 131.7, 124.4, 122.1, 111.1, 54.5, 49.1, 35.0, 33.0, 23.4, 22.8, 13.1, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>17</sub>H<sub>23</sub>N<sub>3</sub>O [M + H]<sup>+</sup>, 271.1805; found 271.1805.

**Formation of Compound 7 by Cyanidation of 2-Iodohuperzine A (3) Using the Rosenmund–von Braun Reaction.** To a solution of 2-iodohuperzine A (**3**, 0.14 mmol, 50 mg) in DMF (3.0 mL) were added CuCN (0.68 mmol, 61 mg) and K<sub>2</sub>CO<sub>3</sub> (0.41 mmol, 56 mg). The mixture was heated at 120 °C for 72 h under an Ar atmosphere. After cooling to room temperature, the reaction mixture was quenched with H<sub>2</sub>O (10 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated under reduced pressure. The crude product was purified by

flash column chromatography (2–7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-cyanohuperzine A (**7**, 19 mg, 53%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-7-methyl-2-oxo-1,2,5,6,9,10-hexahydro-5,9-methanocycloocta[*b*]pyridine-3-carbonitrile (7)**

Yellowish solid; m.p. 244–245 °C;  $[\alpha]_{\text{D}}^{26} -247.5^{\circ}$  (*c* 1.6, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.46 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2225, 1651, 1597, 1566, 1304 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  8.43 (s, 1H), 5.51 (q, *J* = 6.0 Hz, 1H), 5.54 (d, *J* = 6.0 Hz, 1H), 3.60–3.70 (m, 1H), 2.91 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.84 (dd, *J* = 18.0, 1.5 Hz, 1H), 2.11 (s, 2H), 1.69 (d, *J* = 9.0 Hz, 3H), 1.54 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  163.0, 150.9, 147.5, 141.5, 134.1, 124.5, 124.3, 116.2, 112.6, 101.3, 54.5, 49.6, 35.9, 32.6, 22.6, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>16</sub>H<sub>17</sub>N<sub>3</sub>O [M + H]<sup>+</sup>, 268.1444; found 268.1447.

**Formation of Compound 8 by Copper-Catalyzed Heteroarene Amination of 2-Iodohuperzine A (3).** 2-Iodohuperzine A (**3**, 0.14 mmol, 50 mg), copper(I) iodide (1 mg, 4 mol %), and K<sub>2</sub>CO<sub>3</sub> (0.41 mmol, 56 mg) were charged in a 15 mL sealed screw-capped tube under air, and 5.0 mL of aqueous ammonia solution (*ca.* 28%) was added *via* a syringe. The sealed tube was closed tightly after purging with argon gas flow. The reaction mixture was heated at 140 °C and stirred for 72 h. After cooling to room temperature, the reaction mixture was quenched with H<sub>2</sub>O (10 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated under reduced pressure. The crude product was purified by flash column chromatography (7–15% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-aminohuperzine A (**8**, 32 mg, 90%).

**(5*R*,9*R*,*E*)-3,5-Diamino-11-ethylidene-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (8).** Yellowish solid; m.p. 82–84 °C;  $[\alpha]_{\text{D}}^{26} -145.3^{\circ}$  (*c* 1.9, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.11 (10% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  3450, 3295, 1645, 1589, 1454 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CD<sub>3</sub>OD)  $\delta_{\text{H}}$  7.06 (s, 1H), 5.50 (q, *J* = 6.0 Hz, 1H), 5.43 (d, *J* = 3.0 Hz, 1H), 3.60–3.70 (m, 1H), 2.75 (dd, *J* = 18.0, 6.0 Hz, 1H), 2.51 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.23 (s, 2H), 1.71 (d, *J* = 9.0 Hz, 3H), 1.56 (s, 3H); <sup>13</sup>C NMR (75 MHz, CD<sub>3</sub>OD)  $\delta_{\text{C}}$  159.8, 142.0, 137.0, 135.0, 130.5, 125.2, 124.1, 115.1, 112.4, 55.5, 49.4, 35.4, 34.2, 22.7, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>15</sub>H<sub>20</sub>N<sub>3</sub>O [M + H]<sup>+</sup>, 258.1601; found 258.1603.

**Formation of Compound 9 by Copper-Catalyzed Heteroarene Hydroxylation of 2-Iodohuperzine A (3).** 2-Iodohuperzine A (**3**, 0.14 mmol, 50 mg), copper(I) iodide (1 mg, 4 mol %), and K<sub>2</sub>CO<sub>3</sub> (0.41 mmol, 56 mg) were charged in a 15 mL sealed screw-capped tube under air, and 5.0 mL of deionized water was added *via* a syringe. The sealed tube was closed tightly after purging with argon gas flow. The reaction mixture was heated at 140 °C and stirred for 72 h. After cooling to room temperature, the reaction mixture was quenched with H<sub>2</sub>O (10 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, and concentrated under reduced pressure. The crude product was purified by flash column chromatography (7–15% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford 2-hydroxyhuperzine A (**9**, 22 mg, 64%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-3-hydroxy-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (9).** Yellowish solid; m.p. 83–85 °C;  $[\alpha]_{\text{D}}^{26} -151.2^{\circ}$  (*c* 2.5, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.14 (10% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$

3356, 2923, 1648, 1615, 1580, 1439  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (300 MHz,  $(\text{CD}_3)_2\text{SO}$ )  $\delta_{\text{H}}$  7.10 (s, 1H), 5.45 (q,  $J = 6.0$  Hz, 1H), 5.38 (d,  $J = 4.5$  Hz, 1H), 3.40–3.55 (m, 1H), 2.57 (dd,  $J = 18.0, 6.0$  Hz, 1H), 2.40 (d,  $J = 18.0$  Hz, 1H), 1.90–2.10 (m, 2H), 1.62 (d,  $J = 6.0$  Hz, 3H), 1.49 (s, 3H);  $^{13}\text{C}$  NMR (75 MHz,  $(\text{CD}_3)_2\text{SO}$ )  $\delta_{\text{C}}$  158.3, 144.7, 142.1, 133.5, 130.2, 124.4, 121.2, 114.7, 110.4, 53.9, 48.3, 34.1, 32.4, 22.4, 12.1; (+)-HRMS (ESI)  $m/z$  calcd for  $\text{C}_{15}\text{H}_{19}\text{N}_2\text{O}_2$  [ $\text{M} + \text{H}$ ] $^+$ , 259.1447; found 259.1441.

**Formation of Compound 10 by Copper-Catalyzed Heteroarene Methoxylation of 2-Iodohuperzine A (3).** 2-Iodohuperzine A (3, 0.27 mmol, 100 mg), copper(I) iodide (2 mg, 4 mol %), and  $\text{K}_2\text{CO}_3$  (0.81 mmol, 112 mg) were charged in a 15 mL sealed screw-capped tube under air, and 5.0 mL of methanol was added *via* a syringe. The sealed tube was closed tightly after purging with argon gas flow. The reaction mixture was heated at 140  $^\circ\text{C}$  and stirred for 120 h. The crude mixture was filtered through a patch of silica gel and washed with MeOH. The crude product was purified by flash column chromatography (7% v/v MeOH in ethyl acetate) to afford 2-methoxyhuperzine A (10, 49 mg, 66%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-3-methoxy-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[b]pyridin-2(1*H*)-one (10).** Brownish solid; m.p. 90–91  $^\circ\text{C}$ ;  $[\alpha]_{\text{D}}^{26} -89.0^\circ$  ( $c$  2.0,  $\text{CH}_3\text{OH}$ );  $R_f = 0.18$  (7% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  2910, 1647, 1620, 1571, 1462, 1247  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (300 MHz,  $(\text{CD}_3)_2\text{SO}$ )  $\delta_{\text{H}}$  7.22 (s, 1H), 5.48 (q,  $J = 6.0$  Hz, 1H), 5.37 (d,  $J = 3.0$  Hz, 1H), 3.83 (s, 3H), 3.47–3.53 (m, 1H), 2.55 (dd,  $J = 18.0, 6.0$  Hz, 1H), 2.53 (d,  $J = 18.0$  Hz, 1H), 2.05 (s, 2H), 1.61 (d,  $J = 6.0$  Hz, 3H), 1.49 (s, 3H);  $^{13}\text{C}$  NMR (75 MHz,  $(\text{CD}_3)_2\text{SO}$ )  $\delta_{\text{C}}$  157.0, 147.3, 142.1, 133.5, 131.7, 124.4, 120.1, 113.6, 110.4, 55.3, 54.0, 48.2, 34.0, 32.3, 22.4, 12.1; (+)-HRMS (ESI)  $m/z$  calcd for  $\text{C}_{16}\text{H}_{21}\text{N}_2\text{O}_2$  [ $\text{M} + \text{H}$ ] $^+$ , 273.1598; found 273.1597.

**Formation of Compound 11 by Copper-Catalyzed Heteroarene Ethoxylation of 2-Iodohuperzine A (3).** 2-Iodohuperzine A (3, 0.14 mmol, 50 mg), copper(I) iodide (1 mg, 4 mol %), and  $\text{K}_2\text{CO}_3$  (0.41 mmol, 56 mg) were charged in a 15 mL sealed screw-capped tube under air, and 5.0 mL of ethanol was added *via* a syringe. The sealed tube was closed tightly after purging with argon gas flow. The reaction mixture was heated at 140  $^\circ\text{C}$  and stirred for 72 h. The crude mixture was filtered through a patch of silica gel and washed with ethanol. The crude product was purified by flash column chromatography (7–15% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford 2-ethoxyhuperzine A (11, 11 mg, 29%).

**(5*R*,9*R*,*E*)-5-Amino-3-ethoxy-11-ethylidene-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[b]pyridin-2(1*H*)-one (11).** Yellowish solid; m.p. 104  $^\circ\text{C}$ ;  $[\alpha]_{\text{D}}^{26} -61.3^\circ$  ( $c$  1.5,  $\text{CH}_3\text{OH}$ );  $R_f = 0.09$  (10% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  2926, 1647, 1618, 1569, 1455, 1246  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (300 MHz,  $\text{CD}_3\text{OD}$ )  $\delta_{\text{H}}$  7.33 (s, 1H), 5.53 (q,  $J = 6.0$  Hz, 1H), 5.45 (d,  $J = 6.0$  Hz, 1H), 4.04 (q,  $J = 6.0$  Hz, 2H), 3.60–3.70 (m, 1H), 2.76 (dd,  $J = 18.0, 6.0$  Hz, 1H), 2.55 (dd,  $J = 18.0, 3.0$  Hz, 1H), 2.27 (s, 2H), 1.72 (d,  $J = 6.0$  Hz, 3H), 1.57 (s, 3H), 1.41 (t,  $J = 6.0$  Hz, 3H);  $^{13}\text{C}$  NMR (75 MHz,  $\text{CD}_3\text{OD}$ )  $\delta_{\text{C}}$  160.3, 148.3, 140.9, 134.8, 133.9, 125.2, 122.1, 115.7, 112.9, 65.5, 56.0, 48.8, 35.3, 34.0, 22.7, 14.8, 12.5; (+)-HRMS (ESI)  $m/z$  calcd for  $\text{C}_{17}\text{H}_{23}\text{N}_2\text{O}_2$  [ $\text{M} + \text{H}$ ] $^+$ , 287.1754; found 287.1751.

**Formation of Compound 12 by Copper-Catalyzed Heteroarene Alkoxylation of 2-Iodohuperzine A (3).** 2-Iodohuperzine A (3, 0.54 mmol, 200 mg), copper(I) iodide

(4 mg, 4 mol %), and  $\text{K}_2\text{CO}_3$  (1.63 mmol, 225 mg) were charged in a 15 mL sealed screw-capped tube under air, and 5.0 mL of *n*-propanol was added *via* a syringe. The sealed tube was closed tightly after purging with argon gas flow. The reaction mixture was heated at 140  $^\circ\text{C}$  and stirred for 72 h. The crude mixture was filtered through a patch of silica gel and washed with *n*-propanol. The crude product was purified by flash column chromatography (7–15% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford 2-propoxyhuperzine A (12, 107 mg, 66%).

**(5*R*,9*R*,*E*)-5-Amino-11-ethylidene-7-methyl-3-propoxy-5,6,9,10-tetrahydro-5,9-methanocycloocta[b]pyridin-2(1*H*)-one (12).** Yellowish solid; m.p. 109–111  $^\circ\text{C}$ ;  $[\alpha]_{\text{D}}^{26} -67.5^\circ$  ( $c$  3.2,  $\text{CH}_3\text{OH}$ );  $R_f = 0.26$  (10% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  2922, 1650, 1613, 1572, 1455, 1263  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (300 MHz,  $\text{CD}_3\text{OD}$ )  $\delta_{\text{H}}$  7.32 (s, 1H), 5.53 (q,  $J = 6.5$  Hz, 1H), 5.47 (d,  $J = 4.2$  Hz, 1H), 3.94 (t,  $J = 6.6, 2\text{H}$ ), 3.60–3.69 (m, 1H), 2.76 (dd,  $J = 16.5, 6.0$  Hz, 1H), 2.53 (dd,  $J = 16.5, 3.0$  Hz, 1H), 2.29 (s, 2H), 1.86 (sep,  $J = 6.0, 2\text{H}$ ), 1.73 (d,  $J = 6.0$  Hz, 3H), 1.58 (s, 3H), 1.06 (t,  $J = 6.0$  Hz, 3H);  $^{13}\text{C}$  NMR (75 MHz,  $\text{CD}_3\text{OD}$ )  $\delta_{\text{C}}$  160.3, 148.5, 140.6, 134.7, 133.9, 125.2, 121.8, 115.5, 113.1, 71.6, 56.2, 48.7, 35.3, 34.0, 23.3, 22.7, 12.5, 10.8; (+)-HRMS (ESI)  $m/z$  calcd for  $\text{C}_{18}\text{H}_{25}\text{N}_2\text{O}_2$  [ $\text{M} + \text{H}$ ] $^+$ , 301.1911; found 301.1909.

**Formation of Compound 13 by Copper-Catalyzed Heteroarene Alkoxylation of 2-Iodohuperzine A (3).** 2-Iodohuperzine A (3, 0.54 mmol, 200 mg), copper(I) iodide (4 mg, 4 mol %), and  $\text{K}_2\text{CO}_3$  (1.63 mmol, 225 mg) were charged in a 15 mL sealed screw-capped tube under air, and 5.0 mL of *n*-butanol was added *via* a syringe. The sealed tube was closed tightly after purging with argon gas flow. The reaction mixture was heated at 140  $^\circ\text{C}$  and stirred for 72 h. The crude mixture was filtered through a patch of silica gel and washed with *n*-butanol. The crude product was purified by flash column chromatography (7–15% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford 2-butoxyhuperzine A (13, 109 mg, 64%).

**(5*R*,9*R*,*E*)-5-Amino-3-butoxy-11-ethylidene-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[b]pyridin-2(1*H*)-one (13).** Brownish solid; m.p. 110–111  $^\circ\text{C}$ ;  $[\alpha]_{\text{D}}^{26} -127.3^\circ$  ( $c$  1.1,  $\text{CH}_3\text{OH}$ );  $R_f = 0.57$  (10% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  2925, 1648, 1619, 1571, 1464, 1246  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (300 MHz,  $\text{CD}_3\text{OD}$ )  $\delta_{\text{H}}$  7.34 (s, 1H), 5.55 (q,  $J = 6.0$  Hz, 1H), 5.43 (d,  $J = 3.0$  Hz, 1H), 3.97 (t,  $J = 6.0, 2\text{H}$ ), 3.60–3.70 (m, 1H), 2.74 (dd,  $J = 18.0, 6.0$  Hz, 1H), 2.51 (d,  $J = 18.0$  Hz, 1H), 2.22 (s, 1H), 2.21 (s, 1H), 1.75–1.85 (m, 2H), 1.71 (d,  $J = 6.0$  Hz, 3H), 1.57 (s, 3H), 1.42–1.60 (m, 2H), 0.99 (t,  $J = 6.0$  Hz, 3H);  $^{13}\text{C}$  NMR (75 MHz,  $\text{CD}_3\text{OD}$ )  $\delta_{\text{C}}$  160.3, 148.4, 141.9, 135.1, 133.7, 125.2, 123.1, 116.1, 112.6, 69.7, 55.6, 49.3, 35.4, 34.1, 32.1, 22.7, 20.3, 14.2, 12.5; (+)-HRMS (ESI)  $m/z$  calcd for  $\text{C}_{19}\text{H}_{27}\text{N}_2\text{O}_2$  [ $\text{M} + \text{H}$ ] $^+$ , 315.2067; found 315.2067.

**Formation of Compound 14 by *O*-Methylation of Huperzine A (1).** The mixture of HupA (1, 0.12 mmol, 30 mg) and  $\text{Ag}_2\text{CO}_3$  (0.62 mmol, 171 mg) in  $\text{CH}_2\text{Cl}_2$  (2.0 mL) was treated with iodomethane (7.43 mmol, 0.5 mL) slowly at room temperature for 45 h. The crude mixture was filtered through celite and washed with  $\text{CH}_2\text{Cl}_2$  (10 mL). The combined organic layers were washed with sat. NaCl (5 mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ , and concentrated under reduced pressure. The crude product was purified by flash column chromatography (2–4% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford *O*-methylhuperzine A (14, 15 mg, 46%).

**(5*R*,9*R*,*E*)-11-ethylidene-2-methoxy-7-methyl-9,10-dihydro-5,9-methanocycloocta[b]pyridin-5(6*H*)-amine (14).** Clear viscous liquid;  $[\alpha]_{\text{D}}^{26} -92.0^\circ$  ( $c$  1.0,  $\text{CH}_3\text{OH}$ );  $R_f =$

0.40 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2924, 1594, 1576, 1473, 1321, 1256 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.95 (d, *J* = 9.0 Hz, 1H), 6.57 (d, *J* = 9.0 Hz, 1H), 5.49 (q, *J* = 6.0 Hz, 1H), 5.44 (d, *J* = 3.0 Hz, 1H), 3.87 (s, 3H), 3.60–3.70 (m, 1H), 2.99 (dd, *J* = 18.0, 6.0 Hz, 1H), 2.85 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.18 (s, 2H), 1.72 (d, *J* = 6.0 Hz, 3H), 1.51 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  162.7, 153.6, 143.7, 136.7, 133.5, 133.0, 125.1, 110.7, 108.2, 55.4, 53.5, 50.7, 40.5, 34.0, 22.8, 12.6; (+)-HRMS (ESI) *m/z* calcd for C<sub>16</sub>H<sub>21</sub>N<sub>2</sub>O [M + H]<sup>+</sup>, 257.1648; found 257.1649.

**Formation of Compounds 15–17 by *N*-Methylation of Huperzine A (1).** The mixture of HupA (1, 1.03 mmol, 250 mg) and Ag<sub>2</sub>CO<sub>3</sub> (5.16 mmol, 1.42 g) in CH<sub>2</sub>Cl<sub>2</sub> (5.0 mL) was treated with iodomethane (61.90 mmol, 3.9 mL) slowly at room temperature for 72 h. The crude mixture was filtered through celite and washed with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (5 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and concentrated under reduced pressure. The crude product was purified by flash column chromatography (2–4% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford *N,N,O*-trimethylhuperzine A (15, 56 mg, 19%), *N,N,N'*-trimethylhuperzine A (16, 76 mg, 26%), and *N,N*-dimethylhuperzine A (17, 28 mg, 10%).

**(5*R*,9*R*,*E*)-11-Ethylidene-2-methoxy-*N,N*,7-trimethyl-9,10-dihydro-5,9-methanocycloocta[*b*]pyridin-5(6*H*)-amine (15).** Clear viscous liquid; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –15.0° (*c* 2.0, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.80 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2924, 1592, 1575, 1473, 1359, 1254 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.63 (d, *J* = 6.0 Hz, 1H), 6.51 (d, *J* = 6.0 Hz, 1H), 5.48 (q, *J* = 6.0 Hz, 1H), 5.35 (d, *J* = 3.0 Hz, 1H), 3.87 (s, 3H), 3.54–3.64 (m, 1H), 2.94 (dd, *J* = 18.0, 6.0 Hz, 1H), 2.87 (s, 3H), 2.74 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.64 (s, 1H), 2.12 (s, 3H), 2.10 (s, 1H), 1.69 (d, *J* = 6.0 Hz, 3H), 1.50 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  162.2, 154.2, 138.5, 137.5, 133.9, 132.5, 124.9, 113.3, 107.8, 63.3, 53.3, 47.9, 40.6, 39.9, 39.4, 34.5, 23.2, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>18</sub>H<sub>25</sub>N<sub>2</sub>O [M + H]<sup>+</sup>, 285.1961; found 285.1959.

**(5*R*,9*R*,*E*)-5-(Dimethylamino)-11-ethylidene-1,7-dimethyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (16).** Clear viscous liquid; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –11.0° (*c* 2.5, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.57 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  1649, 1577, 1538, 1416 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.45 (d, *J* = 9.0 Hz, 1H), 6.42 (d, *J* = 12.0 Hz, 1H), 5.42 (q, *J* = 6.0 Hz, 1H), 5.28 (d, *J* = 3.0 Hz, 1H), 3.50–3.60 (m, 1H), 3.41 (s, 3H), 2.80 (s, 3H), 2.71 (dd, *J* = 15.0, 6.0 Hz, 1H), 2.64 (dd, *J* = 15.0, 3.0 Hz, 2H), 2.13 (s, 3H), 2.03 (d, *J* = 15.0 Hz, 1H), 1.63 (d, *J* = 9.0 Hz, 3H), 1.53 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  163.4, 144.0, 138.5, 136.4, 135.3, 124.0, 123.1, 117.3, 113.9, 62.6, 46.1, 40.0, 39.2, 35.6, 33.6, 31.0, 23.0, 12.5; (+)-HRMS (ESI) *m/z* calcd for C<sub>18</sub>H<sub>25</sub>N<sub>2</sub>O [M + H]<sup>+</sup>, 285.1961; found 285.1959.

**(5*R*,9*R*,*E*)-5-(Dimethylamino)-11-ethylidene-7-methyl-5,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-2(1*H*)-one (17).** Clear viscous liquid; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –51.4° (*c* 1.4, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.02 (7% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  2923, 1654, 1614, 1459, 1260 cm<sup>-1</sup>; <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.57 (d, *J* = 9.0 Hz, 1H), 6.39 (d, *J* = 9.0 Hz, 1H), 5.45 (q, *J* = 6.0 Hz, 1H), 5.35 (s, 1H), 3.50–3.56 (m, 1H), 2.84 (s, 3H), 2.62 (d, *J* = 15.0 Hz, 2H), 2.20 (s, 3H), 2.02 (d, *J* = 18.0 Hz, 2H), 1.65 (d, *J* = 6.0 Hz, 1H), 1.56 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  165.1, 143.6, 141.4, 137.1, 134.8, 124.2, 122.8, 117.0, 114.2, 62.4, 46.3, 40.3, 39.2, 34.9, 33.5, 23.2, 12.5;

(+)-HRMS (ESI) *m/z* calcd for C<sub>17</sub>H<sub>23</sub>N<sub>2</sub>O [M + H]<sup>+</sup>, 271.1805; found 271.1805.

**Formation of Compound 18 by Acetylation of Huperzine A (1).** Hup A 1 (0.33 mmol, 80 mg) was reacted with acetic anhydride (5.67 mmol, 532  $\mu$ L) in CH<sub>2</sub>Cl<sub>2</sub> (2.0 mL) at room temperature for 2 h. The reaction mixture was quenched with H<sub>2</sub>O (10 mL) and extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub> and concentrated under reduced pressure. The crude product was purified by flash column chromatography (5% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>) to afford *N*-acetylhuperzine A (18, 60 mg, 64%).

***N*-(5*R*,9*R*,*E*)-11-Ethylidene-7-methyl-2-oxo-2,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-5(1*H*)-yl)acetamide (18).** White solid; m.p. 180 °C (decomposed); [ $\alpha$ ]<sub>D</sub><sup>26</sup> +15.0° (*c* 1.0, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.20 (5% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  3271, 2932, 1656, 1614, 1555, 1453, 1555, 1453, 1374, 1298, 835 cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.44 (d, *J* = 9.5 Hz, 1H), 6.40 (d, *J* = 9.5 Hz, 1H), 5.43 (br s, 1H), 5.30 (q, *J* = 7.0 Hz, 1H), 3.60 (br s, 1H), 2.96 (dd, *J* = 15.0, 4.8 Hz, 1H), 2.72 (d, *J* = 15.0 Hz, 1H), 2.27 (d, *J* = 6.0 Hz, 1H), 2.23 (d, *J* = 6.0 Hz, 1H), 2.08 (s, 3H), 1.67 (d, *J* = 7.0 Hz, 3H), 1.55 (s, 3H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  175.2, 165.1, 142.5, 139.0, 134.7, 124.8, 120.1, 118.5, 114.5, 112.8, 58.4, 49.4, 34.5, 32.6, 34.3, 22.5, 12.5; HRMS (ESI-TOF) *m/z* calcd for C<sub>17</sub>H<sub>20</sub>N<sub>2</sub>O<sub>2</sub> [M + H]<sup>+</sup>, 285.1525; found 285.1573.

**Formation of Compound 20 by Amine Protection of Huperzine A (1).** To an oven-dried sealed tube were added huperzine A (1) (0.5 mmol, 121 mg), CH<sub>2</sub>Cl<sub>2</sub> (1.1 mL), and Et<sub>3</sub>N (1.0 mmol, 0.14 mL). The reaction mixture was stirred for 5 min and cooled to 0 °C. Trifluoroacetic anhydride (1.5 equiv, 0.1 mL) was added dropwise over 5 min. The resulting mixture was allowed to warm to room temperature and stirred for 20 h. The reaction mixture was washed with sat. NaHCO<sub>3</sub>(aq) (10 mL). The aqueous layer was extracted with EtOAc (10 mL). The combined organic layer was washed with brine (10 mL), dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated *in vacuo* to provide the crude product. The crude mixture was filtered through a patch of silica gel and washed with 10% MeOH in CH<sub>2</sub>Cl<sub>2</sub> to afford *N*-triflate huperzine A (20, 64 mg, 38%).

**(5*R*,9*R*,*E*)-11-Ethylidene-7-methyl-2-oxo-5-((2,2,2-trifluoro-1,1-dioxo-1 $\lambda^7$ -ethoxy)amino)-1,2,5,6,9,10-hexahydro-5,9-methanocycloocta[*b*]pyridine (20).** White solid; m.p. 192–195 °C; [ $\alpha$ ]<sub>D</sub><sup>26</sup> –9.6° (*c* 2.3, CH<sub>3</sub>OH); *R*<sub>f</sub> = 0.30 (10% v/v MeOH in CH<sub>2</sub>Cl<sub>2</sub>); IR (neat)  $\nu$  3217, 3026, 2908, 1728, 1651, 1612, 1550, 1453, 1186, 1151, 834, 727 cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta_{\text{H}}$  7.35 (d, *J* = 9.5 Hz, 1H), 6.43 (d, *J* = 9.5, 1H), 6.31 (s, 1H), 5.45 (br s, 1H), 5.24 (q, *J* = 8.0 Hz, 1H), 3.64 (br. s, 1H), 2.97 (dd, *J* = 17.0, 5.0 Hz, 1H), 2.71 (d, *J* = 16.0, 1H), 2.40 (d, *J* = 16.0 Hz, 2H), 1.69 (d, *J* = 8.0 Hz, 3H), 1.58 (s, 3H); <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>)  $\delta_{\text{C}}$  165.0, 155.8 (q, 144.4), 143.2, 138.2, 133.3, 132.4, 124.6, 118.2, 115.7 (q, 62.4), 113.3, 59.4, 46.9, 34.4, 32.6, 22.5, 12.5; HRMS (ESI-TOF) *m/z* calcd for C<sub>17</sub>H<sub>18</sub>F<sub>3</sub>N<sub>2</sub>O<sub>2</sub>[M + H]<sup>+</sup>, 339.1315; found 339.1312.

**Formation of Compound 21 by Amine Protection of Huperzine A (1).** Huperzine A (1) (0.21 mmol, 50 mg) was reacted with Boc<sub>2</sub>O (1.03 mmol, 225 mg), DMAP (0.08 mmol, 10 mg), and Et<sub>3</sub>N (0.62 mmol, 86  $\mu$ L) in CH<sub>2</sub>Cl<sub>2</sub> (1.0 mL) at room temperature for 1.5 h. H<sub>2</sub>O (10 mL) was added, and the mixture was extracted three times with CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The combined organic layers were washed with sat. NaCl (10 mL),

then dried over anhydrous  $\text{Na}_2\text{SO}_4$ , and evaporated under reduced pressure. The crude product was purified by flash column chromatography (10% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford *N*-*tert*-butyloxycarbonylhuperzine A (**21**, 20 mg, 29%).

*tert*-Butyl-((5*R*,9*R*,*E*)-11-ethylidene-7-methyl-2-oxo-2,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-5(1*H*)-yl)carbamate (**21**). White solid;  $[\alpha]_{\text{D}}^{26} -56.4^\circ$  (*c* 1.1,  $\text{CH}_3\text{OH}$ );  $R_f = 0.20$  (10% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  2927, 1758, 1584, 1229, 1143  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$  8.21 (d, *J* = 9.0 Hz, 1H), 6.95 (d, *J* = 9.0 Hz, 1H), 5.52 (q, *J* = 6.0 Hz, 1H), 5.44 (d, *J* = 6.0 Hz, 1H), 3.60–3.69 (m, 1H), 3.05 (dd, *J* = 18.0, 6.0 Hz, 1H), 2.94 (dd, *J* = 18.0, 3.0 Hz, 1H), 2.22 (br s, 2H), 1.73 (d, *J* = 9.0 Hz, 3H), 1.54 (s, 9H), 1.51 (s, 3H);  $^{13}\text{C}$  NMR (75 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$  155.91, 155.57, 151.46, 142.69, 139.08, 137.66, 133.2, 125.0, 113.4, 111.5, 83.8, 55.6, 50.7, 40.1, 33.7, 27.7 (3C), 22.5, 12.5. (+)-HRMS (ESI) *m/z* calcd for  $\text{C}_{20}\text{H}_{27}\text{N}_2\text{O}_3$  [*M* + *H*] $^+$ , 343.2016; found 343.2018.

**Formation of Compound 22 by Bromination of *N*-Acetylhuperzine A (**18**).** *N*-Acetylhuperzine A (**18**) (0.07 mmol, 19 mg) was reacted with  $\text{CuBr}_2$  (0.08 mmol, 19 mg) in acetonitrile (2.0 mL) under an Ar atmosphere at 50 °C for 17 days. The reaction mixture was quenched with  $\text{H}_2\text{O}$  (10 mL) and extracted three times with  $\text{CH}_2\text{Cl}_2$  (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ , and evaporated under reduced pressure. The crude product was purified by flash column chromatography (5% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford 2-bromo-*N*-acetylhuperzine A (**22**, 21 mg, 86%).

*N*-((5*R*,9*R*,*E*)-3-Bromo-11-ethylidene-7-methyl-2-oxo-2,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-5(1*H*)-yl)acetamide (**22**). Pale yellow solid; m.p. 180 °C (decomposed);  $[\alpha]_{\text{D}}^{26} -29.0^\circ$  (*c* 4.2,  $\text{CH}_3\text{OH}$ );  $R_f = 0.70$  (5% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  3282, 2929, 1646, 1616, 1548, 1450, 1377, 1294, 1258, 1024, 952, 789, 735  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$  7.74 (s, 1H), 5.45 (d, *J* = 4.8 Hz, 1H), 5.29 (q, *J* = 6.8 Hz, 1H), 3.63 (br s, 1H), 2.93 (dd, *J* = 5.6, 4.4 Hz, 1H), 2.63 (d, *J* = 15.6 Hz, 1H), 2.21 (d, *J* = 12.0 Hz, 1H), 2.11 (s, 1H), 2.08 (s, 3H), 1.60 (d, *J* = 6.8 Hz, 3H), 1.56 (s, 3H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$  167.7, 159.7, 141.1, 139.7, 132.7, 131.4, 123.8, 119.9, 112.3, 57.0, 33.3, 31.5, 29.1, 23.2, 21.5, 21.4, 11.5; HRMS (ESI-TOF) *m/z* calcd for  $\text{C}_{17}\text{H}_{20}^{79}\text{BrN}_2\text{O}_2$  [*M* + *H*] $^+$ , 363.0630; found 363.0703.

**Formation of Compound 23 by Iodination of *N*-Acetylhuperzine A (**18**).** *N*-Acetylhuperzine A (**18**) (0.11 mmol, 28 mg) was reacted with NIS (0.17, 15 mg) in  $\text{CH}_2\text{Cl}_2$  (1.0 mL) at room temperature for 5.5 h. The reaction mixture was quenched with  $\text{H}_2\text{O}$  (10 mL) and extracted three times with  $\text{CH}_2\text{Cl}_2$  (10 mL). The combined organic layers were washed with sat. NaCl (10 mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ , and evaporated under reduced pressure. The crude product was purified by flash column chromatography (7% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ) to afford 2-iodo-*N*-acetylhuperzine A (**23**, 20 mg, 45%).

*N*-((5*R*,9*R*,*E*)-11-Ethylidene-3-iodo-7-methyl-2-oxo-2,6,9,10-tetrahydro-5,9-methanocycloocta[*b*]pyridin-5(1*H*)-yl)acetamide (**23**). Pale yellow solid; m.p. 200 °C (decomposed);  $[\alpha]_{\text{D}}^{26} -97.5^\circ$  (*c* 3.2,  $\text{CH}_3\text{OH}$ );  $R_f = 0.40$  (5% v/v MeOH in  $\text{CH}_2\text{Cl}_2$ ); IR (neat)  $\nu$  3277, 3049, 2926, 2858, 1636, 1612, 1542, 1423, 1264, 1182, 732, 7014,  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{H}}$  7.89 (s, 1H), 5.46 (d, *J* = 8.4 Hz, 1H), 5.22 (q, *J* = 8.8 Hz, 1H), 3.50 (t, *J* = 4.0 Hz, 1H), 2.85 (dd, *J* = 12.8, 4.4 Hz, 1H), 2.55 (d, *J* = 16.8 Hz, 1H), 2.19 (s, 1H), 2.08 (s,

3H), 1.60 (d, *J* = 6.8 Hz, 3H), 1.51 (s, 3H);  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta_{\text{C}}$  169.0, 161.8, 147.5, 143.4, 134.0, 132.5, 124.8, 123.0, 113.3, 58.0, 47.8, 34.4, 32.5, 29.7, 24.3, 22.5, 12.5; HRMS (ESI-TOF) *m/z* calcd for  $\text{C}_{17}\text{H}_{20}^{127}\text{I}_2\text{N}_2\text{O}_2$  [*M* + *H*] $^+$ , 411.0564; found 411.0562.

**Biological Studies. AChE and BChE Inhibition Assays.** The AChE inhibition activity of HupA derivatives were measured using the spectrometric method of Ellman.<sup>48</sup> Briefly, 20  $\mu\text{L}$  of the tested compound solution (dissolved in methanol with DMSO as a solubilizing agent), 100  $\mu\text{L}$  of phosphate buffer (pH 8.0), and 20  $\mu\text{L}$  of 3.3 mM 5,5'-dithiobis-2-nitrobenzoic acid (DTNB) aqueous solution were transferred into a 96-well plate. A total of 40  $\mu\text{L}$  of 0.25 U/mL electric eel acetylcholinesterase (*ee*AChE, Sigma-Aldrich) solution was added into the mixture and incubated at 37 °C for 20 min. After incubation, 20  $\mu\text{L}$  of 5 mM acetylthiocholine iodide (ATCI) was added and shaken gently. The absorbance was measured at 412 nm every 20 s for 3 min using a microplate reader with a UV–visible spectrometer to obtain the enzymatic reaction rate (maximal velocity,  $V_{\text{max}}$ ). Phosphate buffer (pH 8.0) instead of AChE was used as the blank to obtain the enzymatic reaction rate of the blank ( $V_{\text{blank}}$ ). Donepezil hydrochloride monohydrate instead of the tested compound was used as the positive control, and methanol was used as the negative control ( $V_{\text{control}}$ ).

The percentage inhibition activity of AChE of all HupA analogs was calculated using the following equation:

$$\% \text{inhibition} = \frac{(V_{\text{control}} - V_{\text{blank}}) - (V_i - V_{\text{blank}})}{(V_{\text{control}} - V_{\text{blank}})} \times 100$$

where  $V_{\text{control}}$  = enzymatic reaction rate of control,  $V_{\text{blank}}$  = enzymatic reaction rate of blank, and  $V_i$  = enzymatic reaction rate of tested compound.

The inhibition activities of AChE of all HupA analogs were expressed as the half-maximal inhibitory concentration ( $\text{IC}_{50}$ ) using 8–10 different concentrations of each HupA analog. The compounds with  $\text{IC}_{50}$  concentration more than 1000  $\mu\text{M}$  was considered as inactive. All determinations were carried out in triplicate and expressed as mean  $\pm$  standard error of the mean (S.E.M.). For the BChE inhibition assay, experimental procedures and calculations of the BChE inhibition activity of HupA analogs were conducted similar to the methods described previously, but using butyrylthiocholine iodide (BTCl) instead of ATCI and BChE from equine serum (*eq*-BChE) instead of *ee*AChE.

**Cell Culture.** The normal human lung fibroblast cell line (IMR90) was purchased from the American Type Culture Collection (ATCC; Manassas, VA, USA). Cells were cultured in DMEM (Dulbecco's Modified Eagle's Medium) supplemented with 10% fetal bovine serum, 100 U/mL penicillin, and 100  $\mu\text{g}/\text{mL}$  streptomycin. Cells were maintained under 5%  $\text{CO}_2$  at 37 °C in humidified air.

**MTT Assay.** IMR90 cells were plated into 96-well plates at a density of  $5 \times 10^4$  cells/well. After 18 h of incubation, the tested samples at the indicated concentrations were added into triplicate wells. Cells were then incubated for 24 h. The cell viability was determined using the MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay. Briefly, the supernatant was removed. A total of 100  $\mu\text{L}$  of the MTT solution (0.5 mg MTT in 1.0 mL complete medium) was added to each well. The cells were incubated at 37 °C for 3 h. The solution was then replaced with 100  $\mu\text{L}$  of DMSO. The

absorbance was measured at 570 nm using a microplate reader (Modular multimode microplate reader, Thermo Scientific). % Cytotoxicity was calculated by comparing the absorbance of the treated wells to the untreated control according to the following equation: %Cytotoxicity =  $[1 - [\text{Abs}(\text{sample})/\text{Abs}(\text{untreated control})]] \times 100$ . The experiment was done in triplicate.

**Data Analysis and Statistical Methods.** The data from the experiment was expressed as mean  $\pm$  standard error of mean (S.E.M). One-way ANOVA and post hoc least-significant difference (LSD) were used to determine the statistical significance of the difference between groups. The association between the estimated  $K_i$  value according to the docking program and calculated  $K_i$  according to *in vitro* results used Pearson and Spearman's correlation analysis.  $p < 0.05$  was considered statistically significant.

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.1c02875>.

Preliminary *in silico* study by using BUDE docking, BUDE docking analysis of preselected huperzine A analogs against hAChE, physiochemical properties of preselected C(2) huperzine A analogs, synthesis of N-protected HupA derivatives 18–23, complete  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopic data of selected C(2) huperzine A and compounds 2–23 (PDF)

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