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Push–pull benzothiazole derivatives as probes for detecting β-amyloid plaques in Alzheimer's brains

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ABSTRACT

We synthesized push–pull benzothiazole derivatives and evaluated their potential as β-amyloid imaging probes. In binding experiments in vitro, the benzothiazoles showed excellent affinity for synthetic Aβ(1-42) aggregates. β-Amyloid plaques in the mouse and human brain were clearly visualized with the benzothiazoles, reflecting the results in vitro. These compounds may be a useful scaffold for the development of novel PET/SPECT and fluorescent tracers for detecting β-amyloid in Alzheimer's brains.

1. Introduction

The formation of β-amyloid (Aβ) plaques is a key neurodegenerative event in Alzheimer's disease (AD).[1,2] Since the imaging of these plaques in vivo may lead to the presymptomatic diagnosis of AD, many molecular probes for this purpose, including PET/SPECT and MRI tracers, have been developed.[3–12] The PET ligand [^{11}C]-2-(4-(methylamino)phenyl)-6-hydroxybenzothiazole (6-OH-BTA-1 or PIB) with a benzothiazole backbone (Fig. 1) has shown particular promise in early clinical trials and is currently being used in a number of human studies.[13–15] In addition to PET/SPECT and MRI probes, much attention has focused on the development of near-infrared fluorescent (NIRF) probes targeting Aβ plaques.[16–18] NIRF probes are typically small molecule fluorescent dyes designed to absorb and emit light in the near-infrared region, where tissue scattering and absorption is lowest. The simple synthesis, low-cost, and long shelf-life of NIRF probes, together with the low-cost of optical imaging devices, present an attractive alternative to MRI and PET/SPECT techniques.

Among NIRF probes reported, to date, NIAD crosses the blood–brain barrier, selectively binds Aβ with high affinity, clears quickly from the brain, and absorbs and emits within the near-infrared region (650–900 nm), often called the 'optical window' (Fig. 1).[17] A series of NIAD derivatives have been designed and synthesized based on a classical push–pull architecture with terminal donor (hydroxy or dimethylamino group) and acceptor (dicyanomethylene group) moieties that are interconnected by a highly polarized bridge (dithienylethenyl group), because various donor and acceptor groups can be used to manipulate the relative energies of HOMO and LUMO and obtain the desired long wavelength of absorption/emission bands.[17]

On the basis of this approach to the molecular design, we planned to develop novel push–pull dyes for detecting Aβ plaques in the brain. We selected benzothiazole or styrylbenzothiazole as the highly polarized bridge, a dimethylamino group as the donor, and a dicyanomethylene group as the acceptor. In the present study, we designed and synthesized two benzothiazole-derived push–pull dyes (PP-BTA-1 and PP-BTA-2 in Fig. 2), and evaluated their biological potential as probes for detecting Aβ plaques in the brain. To our knowledge, this is the first time push–pull benzothiazole derivatives have been proposed as Aβ imaging probes for detecting AD.

2. Results and discussion

The target benzothiazole derivatives were prepared as shown in Schemes 1 and 2. PP-BTA-1 (**4**) was successfully synthesized in a yield of 21.4% according to methods reported previously (Scheme

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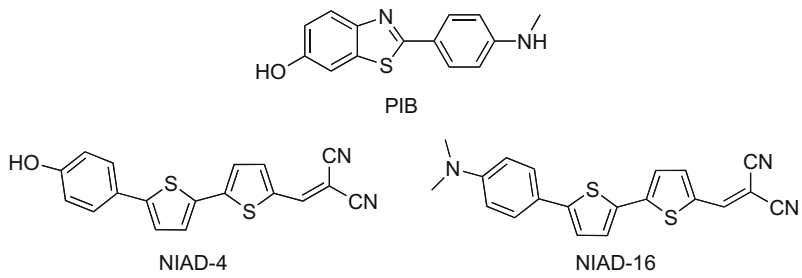


Figure 1. Chemical structures of PIB, NIAD-4 and NIAD-16.

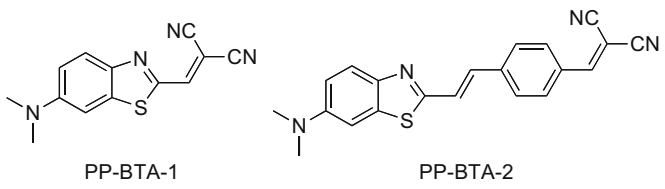
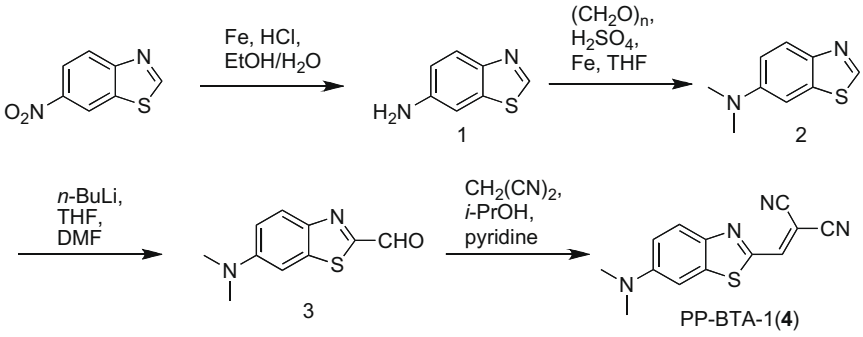


Figure 2. Chemical structures of push–pull benzothiazole derivatives reported in this paper.

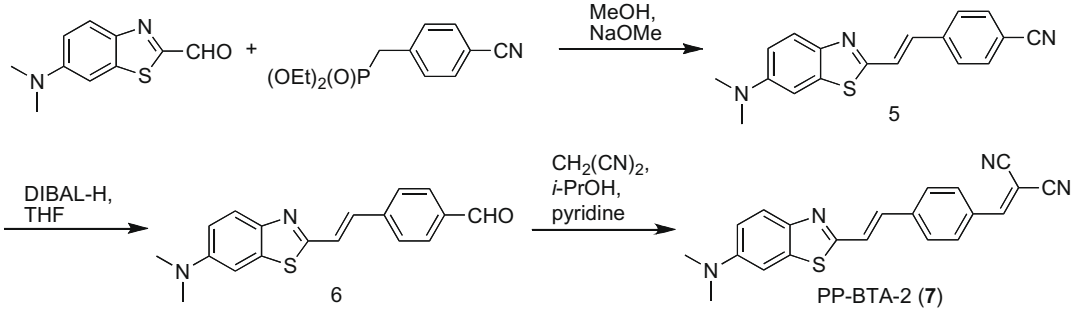
1).[19] The formation of styrylbenzothiazole in the synthesis of PP-BTA-2 (**7**) (Scheme 2) was achieved by a Wadsworth–Emmons reaction between diethyl (4-cyanobenzyl)phosphonate and 6-dimethylaminobenzothiazole-2-carbaldehyde. The desired (*E*)-styrylbenzothiazole derivative was prepared in a yield of 23.0%. The cyano group was converted to a formyl group by a reaction with DIBAL-H as reported.[20] The target PP-BTA-2 was prepared by the condensation of carbaldehyde with malononitrile.

NIRF imaging in vivo requires the development of new fluorescent compounds with optimal fluorescent properties and high affinity for Aβ plaques. First, we evaluated the fluorescent properties (absorption/emission wavelengths) of PP-BTA-1 and PP-BTA-2. PP-BTA-1 and PP-BTA-2 exhibited absorption/emission peaks at 540/634 nm and 410/529 nm in EtOH, respectively. The extension of π-conjugation generally leads to absorption/emission bands with longer wavelengths. However, PP-BTA-2 showed a shorter wavelength than PP-BTA-1 despite a longer π-conjugation. On the other hand, because the wavelength of PP-BTA-1 is close to the near-infrared region, a slight modification should lead to a wavelength appropriate for imaging in vivo. Furthermore, when PP-BTA-1 and PP-BTA-2 existed in a solution containing Aβ(1-42) aggregates, the fluorescence intensity of PP-BTA-1 and PP-BTA-2 increased with the concentration of Aβ(1-42) aggregates, indicating affinity for Aβ aggregates (Fig. 3).

To quantify the affinity of push–pull benzothiazole derivatives for Aβ plaques, we carried out inhibition assays on the binding to Aβ(1-42) aggregates with thioflavin T as a competing ligand. PP-BTA-1 and PP-BTA-2 displaced thioflavin T in a dose-dependent manner, indicating that they have affinity for Aβ(1-42) aggregates (Fig. 4). In addition, this result suggests that PP-BTA-1 and PP-BTA-2 may occupy a binding site on Aβ aggregates similar to that of thioflavin T. The apparent IC_{50} values for PP-BTA-1, PP-BTA-2 and PIB were 0.12, 0.11 and 0.67 μM, respectively (Table 1). The IC_{50} of



Scheme 1.



Scheme 2.

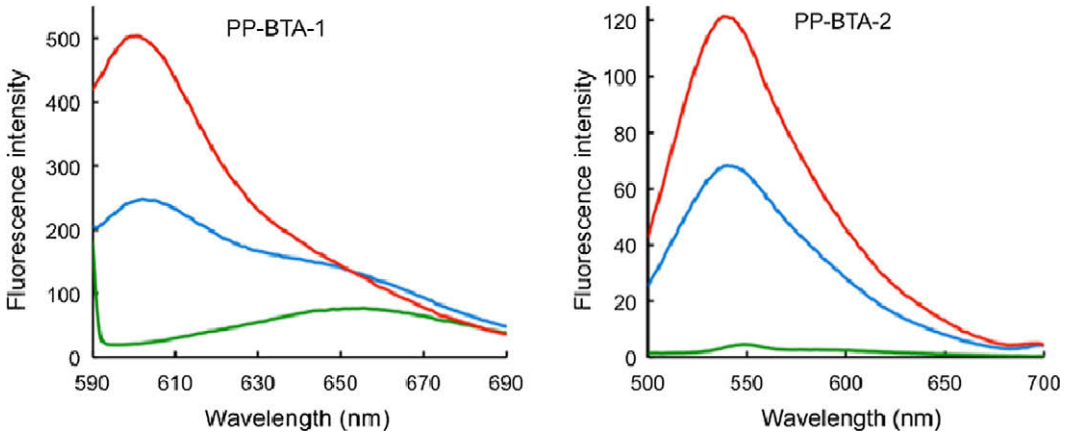


Figure 3. Aβ-dependent change in the fluorescence spectra of PP-BTA-1 and PP-BTA-2. Green, blue and red lines show the fluorescence spectrum of 0, 5 and 10 μg/mL of Aβ(1-42) aggregates, respectively.

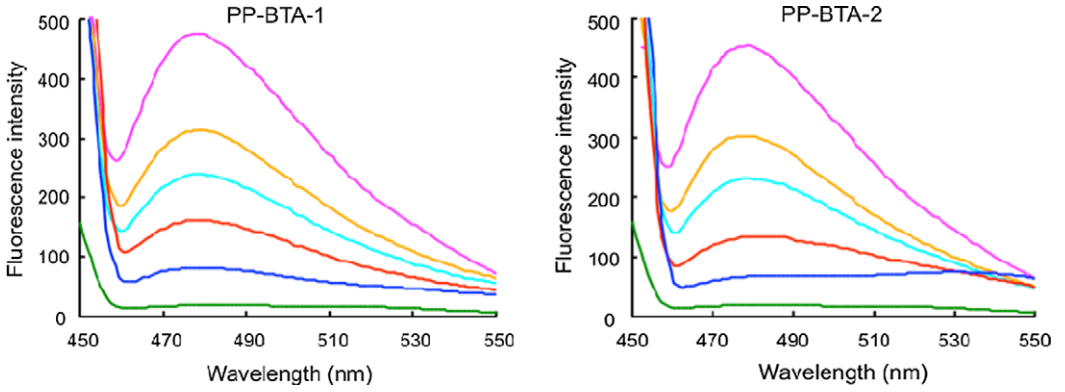


Figure 4. Inhibition assays of PP-BTA-1 and PP-BTA-2 using thioflavin T as the ligand in Aβ(1-42) aggregates. Fluorescence spectral change of thioflavin T (3 μM) upon addition of 0.0611 (orange line), 0.122 (cyan line), 0.486 (red line), or 2.65 (blue line) μM of PP-BTA-1 and PP-BTA-2 to Aβ(1-42) aggregates (10 μg/mL). A pink line shows the fluorescence spectrum of thioflavin T (3 μM) with Aβ(1-42) aggregates. A green line shows the fluorescence spectrum of thioflavin T (3 μM) alone.

Table 1
Apparent inhibition constants (IC_{50}, μM) of benzothiazoles for the binding of thioflavin T to Aβ(1-42) aggregates

Compound	IC_{50}[a] (μM)
PP-BTA-1 (**4**)	0.12 ± 0.001
PP-BTA-2 (**7**)	0.11 ± 0.001
PIB	0.67 ± 0.11

[a] Each value represents the mean ± standard error of the mean for three independent experiments.

PP-BTA-1 and PP-BTA-2 was lower than that of PIB, which is commonly used for clinical research, indicating PP-BTA-1 and PP-BTA-2 to have greater affinity for Aβ(1-42) aggregates. While PP-BTA-1 does not have the phenyl group in the phenylbenzothiazole structure that PIB possesses, it showed stronger binding to Aβ aggregates than PIB. Moreover, benzothiazole is a compact molecule advantageous for penetration of the blood–brain barrier after administration in vivo. These results suggest benzothiazole to be a useful scaffold for the development of Aβ imaging agents in vivo.

Next, the usefulness of PP-BTA-1 and PP-BTA-2 for neuropathological staining of Aβ plaques was investigated in an animal model of AD, the Tg2576 mouse, specifically engineered to overproduce Aβ plaques in the brain. PP-BTA-1 and PP-BTA-2 clearly stained the plaques as reflected by the high affinity for Aβ aggregates in in vitro competition assays (Fig. 5). The labeling pattern was consistent with that observed with thioflavin S. In contrast, wild-type mice displayed no remarkable accumulation of PP-BTA-1 and PP-BTA-2 in brain sections. These results suggest that PP-BTA-1 and PP-BTA-2 show affinity for Aβ plaques in the mouse brain in addition to having affinity for synthetic Aβ(1-42) aggregates.

Furthermore, we also investigated the effectiveness of PP-BTA-1 and PP-BTA-2 for neuropathological staining of Aβ plaques in human AD brain sections (Fig. 6). A previous report suggested the configuration/folding of Aβ plaques in Tg2576 mice to be different from the tertiary/quaternary structure of Aβ plaques in AD brains.[21] Therefore, it is important to evaluate the binding affinity for Aβ plaques in human AD brains. PP-BTA-1 and PP-BTA-2 clearly stained many neuritic plaques in AD brains (Fig. 6A and D). In contrast, no apparent staining was observed in adult normal brain sections (Fig. 6C and F). The labeling pattern was consistent with that observed by immunohistochemical labeling with an antibody specific to Aβ Fig. 6B and E), indicating that PP-BTA-1 and PP-BTA-2 may be applicable for in vivo imaging of Aβ plaques in Alzheimer's brains and deserve further investigation as a potential tool for early diagnosis.

Since PP-BTA-1 and PP-BTA-2 possess a dimethylamino group, they can be used as probes for PET by labeling one of two methyl groups with $^{11}CH_3$. In addition, for the application of push–pull benzothiazole derivatives to optical imaging in vivo, the fine-tuning of absorption/emission wavelengths to a desired region continues by optimizing the combination of donor and acceptor groups.

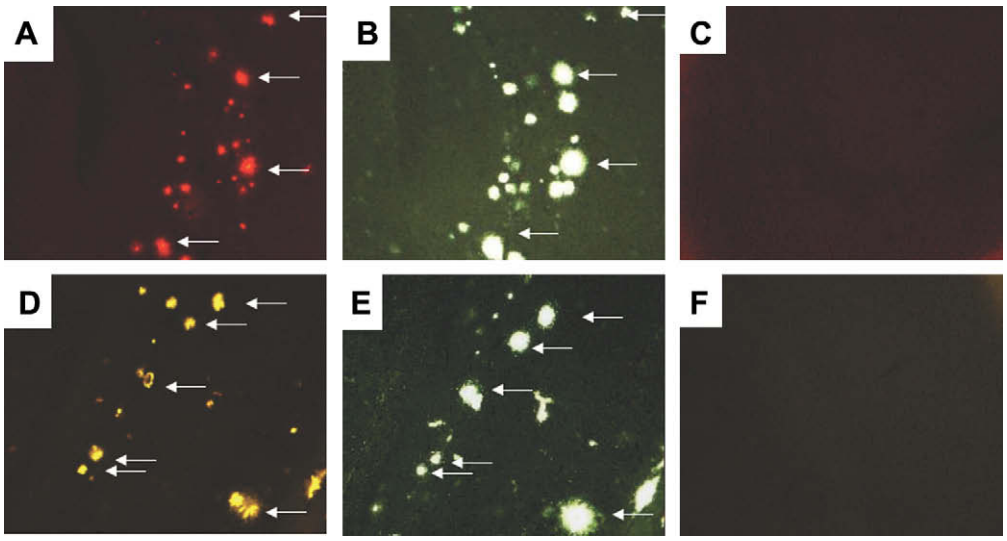


Figure 5. Neuropathological staining of PP-BTA-1 and PP-BTA-2 in 10 μm sections from a mouse model of AD (A and D) and a wild-type mouse (C and F). Aβ plaques labeled with PP-BTA-1 and PP-BTA-2 were confirmed by staining of the serial sections using thioflavin S (B and E).

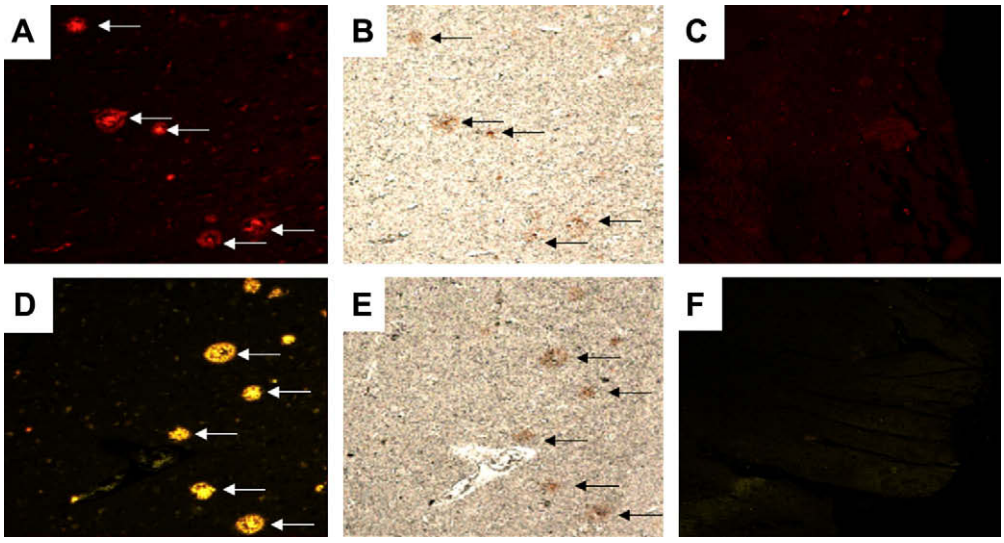


Figure 6. Neuropathological staining of 5 μm AD brain sections from the temporal cortex (A, B, D and E) and adult normal temporal brain sections (C and F). Many neuritic plaques are clearly stained with PP-BTA-1 (A) and PP-BTA-2 (D). Intense fluorescence can be seen in the core of neuritic plaques. Aβ immunostaining with anti Aβ antibodies in the serial sections shows an identical staining pattern of plaques (B and E). No apparent staining was observed in adult normal brain sections (C and F).

3. Conclusion

In conclusion, we successfully designed and synthesized benzothiazole-derived push–pull dyes for imaging Aβ plaques in the brain. In binding experiments in vitro, these benzothiazole compounds showed high affinity for Aβ(1-42) aggregates. PP-BTA-1 and PP-BTA-2 clearly stained Aβ plaques in both mouse brain and human brain, reflecting their affinity for Aβ aggregates in vitro. These findings suggest that additional structural changes on the benzothiazole backbone may be applied to potential Aβ probes for not only optical imaging but also PET and SPECT.

4. Experimental

^{1}H NMR spectra were obtained on a JEOL JNM-LM400 with TMS as an internal standard. Coupling constants are reported in hertz. Multiplicity was defined by s (singlet), d (doublet), t (triplet), br (broad) and m (multiplet). Mass spectra were obtained on a SHIMADZU LCMS-2010 EV. PIB was purchased from ABX (Radeberg, Germany). Other reagents were of reagent grade and used without further purification unless otherwise indicated.

4.1. Chemistry

4.1.1. 1,3-Benzothiazol-6-amine (1)

To a mixture of 6-nitrobenzothiazole (2.5 g, 13.9 mmol) and concentrated HCl (1.93 mL, 22.7 mmol) in 80% EtOH (63 mL) was added powdered iron (3.7 g, 55.6 mmol). The reaction mixture was stirred for 1 h under reflux, and then cooled to room temperature. The precipitate of iron oxides and hydroxy salts was removed by filtration. The solvent was removed and the solid residue was extracted into a heterogeneous mixture of EtOAc (50 mL × 2) and a 10% aqueous solution of Na_2CO_3 (50 mL). The EtOAc extract was dried (Na_2SO_4) and the solvent was removed under vacuum to yield **1** (1.91 g, 91.7%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.70 (s, 1H), 7.89 (d, J = 8.8 Hz, 1H), 7.17 (d, J = 2.4 Hz, 1H), 6.87 (dd, J = 8.8, 2.4 Hz, 1H), 3.85 (br s, 2H). MS m/z 151 [MH^+].

4.1.2. *N,N*-Dimethyl-1,3-benzothiazol-6-amine (2)

A solution of **1** (1.47 g, 9.8 mmol) in THF (40 mL) was slowly added to a stirred mixture of 40% aqueous formaldehyde (7.24 mL, 98 mmol) and 4 M H_2SO_4 (7.95 mL, 29.4 mL). Powdered iron (4.36 g, 78.4 mL) was then added and the mixture was vigorously stirred for 3 h. The precipitate of iron salts was removed by filtration and washed with EtOAc (20 mL × 2). The combined organic solutions were made strongly basic with 1 N NaOH (50 mL) and extracted with EtOAc (50 mL × 2). The combined EtOAc extracts were dried (Na_2SO_4) and the solvent was removed on a rotary vacuum evaporator. The oily residue was purified by silica gel chromatography (hexane/EtOAc = 4:1) to give **2** (460 mg, 26.3%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.67 (s, 1H), 7.95 (d, J = 8.8 Hz, 1H), 7.15 (d, J = 2.4 Hz, 1H), 7.00 (dd, J = 8.8, 2.4 Hz, 1H), 3.04 (s, 6H). MS m/z 179 [MH^+].

4.1.3. 6-(Dimethylamino)-1,3-benzothiazole-2-carbaldehyde (3)

To a vigorously stirred solution of *n*-BuLi (0.5 mL, 2.6 M in hexane, 1.3 mmol) in THF (5.8 mL) at −78 °C under N_2 was added slowly a solution of **2** (220 mg, 1.23 mmol). The reaction mixture was stirred, warmed to −50 °C and after 1 h cooled to −78 °C. To the resulting solution of aryllithium salt was added slowly anhydrous DMF (0.38 mL). The solution was stirred for 2 h, poured into H_2O (9 mL), neutralized with an aqueous saturated solution of NH_4Cl and subsequently extracted with EtOAc (20 mL × 2). The combined extracts were dried over Na_2SO_4 and the solvent was removed under vacuum to give **3** (255 mg, 97.3%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.06 (s, 1H), 8.03 (d, J = 10.0 Hz, 1H), 7.07–7.04 (m, 2H), 3.12 (s, 6H). MS m/z 207 [MH^+].

4.1.4. ((6-(Dimethylamino)-1,3-benzothiazol-2-yl)methylene)-malononitrile (PP-BTA-1, 4)

A solution of **3** (124 mg, 0.6 mmol), malononitrile (60 mg, 0.9 mmol) and pyridine (0.12 mL) in 2-propanol (7.2 mL) was stirred and refluxed for 30 min. The mixture was poured into H_2O (20 mL) and extracted with $CHCl_3$ (20 mL × 3). The combined extracts were dried over Na_2SO_4 and the solvent was removed under vacuum to give **4** (152 mg, 91.7%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.99 (s, 1H), 7.99 (d, J = 9.2 Hz, 1H), 7.08 (dd, J = 9.2, 2.4 Hz, 1H), 7.02 (d, J = 2.4 Hz, 1H), 3.16 (s, 6H). MS m/z 255 [MH^+]. Anal. Calcd for $C_{13}H_{10}N_4S$: C, 61.40; H, 3.96; N, 22.03; S, 12.61. Found: C, 61.34; H, 3.84; N, 21.82; S, 12.64.

4.1.5. 4-((*E*)-2-(6-(Dimethylamino)-1,3-benzothiazol-2-yl) vinyl)benzonitrile (5)

To a solution of (4-cyanobenzyl)phosphonate (403.6 mg, 1.6 mmol) in MeOH (12.8 mL) was added NaOMe (0.632 mL). The mixture was cooled in an ice bath, and stirred under reflux for 3 h after the addition of **3** (330 mg, 1.6 mmol). The solid that formed in the reaction mixture was filtered to give **5** (385 mg, 78.8%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, J = 9.6 Hz, 1H), 7.64 (dd, J = 21.2, 8.0 Hz, 4H), 7.45 (d, J = 16.4 Hz, 1H), 7.32 (d, J = 16.4 Hz, 1H), 7.06 (d, J = 2.8 Hz, 1H), 6.95 (dd, J = 9.6, 2.8 Hz, 1H), 3.06 (s, 6H). MS m/z 306 [MH^+].

4.1.6. 4-((*E*)-2-(6-(Dimethylamino)-1,3-benzothiazol-2-yl) vinyl)benzaldehyde (6)

To a solution of **5** (61 mg, 0.2 mmol) in THF (3.3 mL) was added DIBAL-H (1 M in hexane, 0.5 mL) at −78 °C. The reaction mixture was stirred at room temperature overnight. Thereafter, 10% acetic acid (15 mL) was added and the mixture was extracted with $CHCl_3$ (20 mL × 2). After the organic layer was washed with saline, the combined extracts were dried over Na_2SO_4. The residue was purified by silica gel chromatography (hexane/EtOAc = 2:1) to give **6** (28 mg, 45.4%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.02 (s, 1H), 7.90 (d, J = 8.4 Hz, 2H), 7.85 (d, J = 8.2 Hz, 1H), 7.67 (d, J = 8.4 Hz, 2H), 7.50 (d, J = 16.4 Hz, 1H), 7.38 (d, J = 16.4 Hz, 1H), 7.07 (d, J = 2.4 Hz, 1H), 6.96 (dd, J = 8.8, 2.4 Hz, 1H), 3.06 (s, 6H). MS m/z 309 [MH^+].

4.1.7. 4-((*E*)-2-(6-(Dimethylamino)-1,3-benzothiazol-2-yl) vinyl)benzylidene)malononitrile (PP-BTA-2, 7)

The same reaction as described above to prepare **5** was used, and 45 mg of **7** was obtained in a 63.5% yield from **6**. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, J = 8.4 Hz, 2H), 7.86 (d, J = 8.8 Hz, 1H), 7.73 (s, 1H), 7.68 (d, J = 8.4 Hz, 2H), 7.53 (d, J = 16.4 Hz, 1H), 7.35 (d, J = 16.4 Hz, 1H), 7.08 (s, 1H), 6.97 (d, J = 10.0 Hz , 1H), 3.08 (s, 6H). MS m/z 357 [MH^+]. Anal. Calcd for $C_{21}H_{16}N_4S$: C, 70.76; H, 4.52; N, 15.72; S, 9.00. Found: C, 70.48; H, 4.57; N, 15.43; S, 8.99.

4.2. Fluorescence experiments

PP-BTA-1 and PP-BTA-2 were dissolved in 5% EtOH at 10 μM. The fluorescence of PP-BTA-1 and PP-BTA-2 was measured with a spectrophotometer (RF-1500, Shimadzu, Japan). For some measurements, the spectra of PP-BTA-1 and PP-BTA-2 were determined with or without Aβ(1-42) aggregates (0, 5 and 10 μM).

4.3. Binding experiments using Aβ(1-42) aggregates

A solid form of Aβ(1-42) was purchased from Peptide Institute (Osaka, Japan). Aggregation was carried out by gently dissolving the peptide (0.25 mg/mL) in a buffer solution (pH 7.4) containing 10 mM sodium phosphate and 1 mM EDTA. The solution was incubated at 37 °C for 42 h with gentle and constant shaking. Thioflavin-T was used as the tracer for the competition binding experiments. A mixture (3.6 mL of 10% EtOH) containing PP-BTA-1, PP-BTA-2 and PIB (final concn 61.1 nM−5.48 μM), thioflavin-T (final concn 3 μM), and Aβ(1-42) aggregates (final concn 10 μg/mL) was incubated at room temperature for 10 min. Fluorescence intensity at an excitation wavelength of 445 nm was plotted, and values for the apparent half-maximal inhibitory concentration (IC_{50}) were determined from a calibration curve of fluorescence intensity at 478 nm in three independent experiments.

4.4. Staining of Aβ plaques in Tg2576 mouse brain sections

The experiments with animals were conducted in accordance with our institutional guidelines and approved by the Kyoto University Animal Care Committee. The Tg2576 transgenic mice (female, 27-month-old) and wild-type mice (female, 27-month-old) were used as the Alzheimer's model and control mice, respectively. After the mice were sacrificed by decapitation, the brains were immediately removed and frozen in powdered dry ice. The frozen blocks were sliced into serial sections, 10 μm thick. Each slide was incubated with a 50% EtOH solution (100 μM) of PP-BTA-1 and PP-BTA-2 for 10 min. The sections were washed in 50% EtOH for 1 min two times, and examined using a microscope (Nikon Eclipse 80i) equipped with a G-2A filter set (excitation, 510–560 nm; diachronic mirror, 575 nm; longpass filter, 470 nm) for PP-BTA-1, and a B-2A filter set (excitation, 450–480 nm; diachronic mirror, 505 nm; longpass filter, 520 nm) for PP-BTA-2. Thereafter, the serial sections were also stained with thioflavin S, a pathological dye commonly used for staining Aβ plaques in the brain, and examined using a microscope (Nikon Eclipse 80i) equipped with a BV-2A filter set (excitation, 400–440 nm; diachronic mirror, 455 nm; longpass filter, 470 nm).

4.5. Staining of Aβ plaques in human AD brain sections

Postmortem brain tissues from an autopsy-confirmed case of AD (73-year-old male) and a control subject (36-year-old male) were

obtained from BioChain Institute Inc. The sections were incubated with PP-BTA-1 and PP-BTA-2 (50% EtOH, 100 μM) for 10 min at room temperature. The sections were washed in 50% EtOH for 1 min two times, and examined using a microscope (Nikon Eclipse 80i) equipped with a G-2A filter set (excitation, 510–560 nm; diachronic mirror, 575 nm; longpass filter, 470 nm) for PP-BTA-1, and a B-2A filter set (excitation, 450–480 nm; diachronic mirror, 505 nm; longpass filter, 520 nm) for PP-BTA-2. The presence and localization of plaques on the same sections were confirmed with immunohistochemical staining using a monoclonal Aβ antibody, BC05 (Wako).

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References and notes

1. Klunk, W. E. *Neurobiol. Aging* **1998**, *19*, 145.
2. Selkoe, D. J. *Physiol. Rev.* **2001**, *81*, 741.
3. Shoghi-Jadid, K.; Small, G. W.; Agdeppa, E. D.; Kepe, V.; Ercoli, L. M.; Siddarth, P.; Read, S.; Satyamurthy, N.; Petric, A.; Huang, S. C.; Barrio, J. R. *Am. J. Geriatr. Psychiat.* **2002**, *10*, 24.
4. Mathis, C. A.; Wang, Y.; Holt, D. P.; Huang, G. F.; Debnath, M. L.; Klunk, W. E. *J. Med. Chem.* **2003**, *46*, 2740.
5. Ono, M.; Wilson, A.; Nobrega, J.; Westaway, D.; Verhoeff, P.; Zhuang, Z. P.; Kung, M. P.; Kung, H. F. *Nucl. Med. Biol.* **2003**, *30*, 565.
6. Klunk, W. E.; Engler, H.; Nordberg, A.; Wang, Y.; Blomqvist, G.; Holt, D. P.; Bergstrom, M.; Savitcheva, I.; Huang, G. F.; Estrada, S.; Ausen, B.; Debnath, M. L.; Barletta, J.; Price, J. C.; Sandell, J.; Lopresti, B. J.; Wall, A.; Koivisto, P.; Antoni, G.; Mathis, C. A.; Langstrom, B. *Ann. Neurol.* **2004**, *55*, 306.
7. Verhoeff, N. P.; Wilson, A. A.; Takeshita, S.; Trop, L.; Hussey, D.; Singh, K.; Kung, H. F.; Kung, M. P.; Houle, S. *Am. J. Geriatr. Psychiat.* **2004**, *12*, 584.
8. Small, G. W.; Kepe, V.; Ercoli, L. M.; Siddarth, P.; Bookheimer, S. Y.; Miller, K. J.; Lavretsky, H.; Burggren, A. C.; Cole, G. M.; Vinters, H. V.; Thompson, P. M.; Huang, S. C.; Satyamurthy, N.; Phelps, M. E.; Barrio, J. R. *N. Eng. J. Med.* **2006**, *355*, 2652.
9. Kudo, Y.; Okamura, N.; Furumoto, S.; Tashiro, M.; Furukawa, K.; Maruyama, M.; Itoh, M.; Iwata, R.; Yanai, K.; Arai, H. *J. Nucl. Med.* **2007**, *48*, 553.
10. Rowe, C. C.; Ackerman, U.; Browne, W.; Mulligan, R.; Pike, K. L.; O'Keefe, G.; Tochon-Danguy, H.; Chan, G.; Berlangieri, S. U.; Jones, G.; Dickinson-Rowe, K. L.; Kung, H. P.; Zhang, W.; Kung, M. P.; Skovronsky, D.; Dyrks, T.; Holl, G.; Krause, S.; Friebe, M.; Lehman, L.; Lindemann, S.; Dinkelborg, L. M.; Masters, C. L.; Villemagne, V. L. *Lancet. Neurol.* **2008**, *7*, 129.
11. Higuchi, M.; Iwata, N.; Matsuba, Y.; Sato, K.; Sasamoto, K.; Saido, T. C. *Nat. Neurosci.* **2005**, *8*, 527.
12. Poduslo, J. F.; Curran, G. L.; Peterson, J. A.; McCormick, D. J.; Fauq, A. H.; Khan, M. A.; Wengenack, T. M. *Biochemistry* **2004**, *43*, 6064.
13. Bacskai, B. J.; Frosch, M. P.; Freeman, S. H.; Raymond, S. B.; Augustinack, J. C.; Johnson, K. A.; Irizarry, M. C.; Klunk, W. E.; Mathis, C. A.; Dekosky, S. T.; Greenberg, S. M.; Hyman, B. T.; Growdon, J. H. *Arch. Neurol.* **2007**, *64*, 431.
14. Johnson, K. A.; Gregas, M.; Becker, J. A.; Kinnecom, C.; Salat, D. H.; Moran, E. K.; Smith, E. E.; Rosand, J.; Rentz, D. M.; Klunk, W. E.; Mathis, C. A.; Price, J. C.; Dekosky, S. T.; Fischman, A. J.; Greenberg, S. M. *Ann. Neurol.* **2007**, *62*, 229.
15. Pike, K. E.; Savage, G.; Villemagne, V. L.; Ng, S.; Moss, S. A.; Maruff, P.; Mathis, C. A.; Klunk, W. E.; Masters, C. L.; Rowe, C. C. *Brain* **2007**, *130*, 2837.
16. Hintersteiner, M.; Enz, A.; Frey, P.; Jaton, A. L.; Kinzy, W.; Kneuer, R.; Neumann, U.; Rudin, M.; Staufenbiel, M.; Stoeckli, M.; Wiederhold, K. H.; Gremlich, H. U. *Nat. Biotechnol.* **2005**, *23*, 577.
17. Nesterov, E. E.; Skoch, J.; Hyman, B. T.; Klunk, W. E.; Bacskai, B. J.; Swager, T. M. *Angew. Chem., Int. Ed. Engl.* **2005**, *44*, 5452.
18. Raymond, S. B.; Skoch, J.; Hills, I. D.; Nesterov, E. E.; Swager, T. M.; Bacskai, B. J. *Eur. J. Nucl. Med. Mol. Imaging* **2008**, *35*, S93.
19. Hrobarik, P.; Sigmundova, I.; Zahradnik, P. *Synthesis* **2005**, *4*, 600.
20. Cho, B. R.; Chajara, K.; Jung, H.; Son, K. H.; Jeon, S. J. *Org. Lett.* **2002**, *4*, 1703.
21. Toyama, H.; Ye, D.; Ichise, M.; Liow, J. S.; Cai, L.; Jacobowitz, D.; Musachio, J. L.; Hong, J.; Crescenzo, M.; Tipre, D.; Lu, J. Q.; Zoghbi, S.; Vines, D. C.; Seidel, J.; Katada, K.; Green, M. V.; Pike, V. W.; Cohen, R. M.; Innis, R. B. *Eur. J. Nucl. Med. Mol. Imaging* **2005**, *32*, 593.