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Recommended Citation
Huynh, Truc T; Wang, Yujue; Terpstra, Karna; Cho, Hong-Jun; Mirica, Liviu M; and Rogers, Buck E, "68Ga-labeled benzothiazole derivatives for imaging Aβ plaques in cerebral amyloid angiopathy," ACS Omega. 7, 23, 20339 - 20346. (2022).  
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68Ga-Labeled Benzothiazole Derivatives for Imaging Aβ Plaques in Cerebral Amyloid Angiopathy

Truc T. Huynh, Yujue Wang, Karna Terpstra, Hong-Jun Cho, Liviu M. Mirica,* and Buck E. Rogers*

ABSTRACT: Timely diagnostic imaging plays a crucial role in managing cerebral amyloid angiopathy (CAA)—the condition in which amyloid β is deposited on blood vessels. To selectively map these amyloid plaques, we have designed amyloid-targeting ligands that can effectively complex with 68Ga3+ while maintaining good affinity for amyloid β. In this study, we introduced novel 1,4,7-triazacyclononane-based bifunctional chelators (BFCs) that incorporate a benzothiazole moiety as the Aβ-binding fragment and form charged and neutral species with 68Ga3+. In vitro autoradiography using 5xFAD and WT mouse brain sections (11-month-old) suggested strong and specific binding of the 68Ga complexes to amyloid β. Biodistribution studies in CD-1 mice revealed a low brain uptake of 0.10–0.33% ID/g, thus suggesting 68Ga-labeled novel BFCs as promising candidates for detecting CAA.

INTRODUCTION

Cerebral amyloid angiopathy (CAA) is the condition in which amyloid β is built on the walls of the arteries in the brain, thus allowing blood to leak out and causing hemorrhagic strokes in the elderly.1,2 This differs from Alzheimer’s disease (AD) in which amyloid β is deposited in the brain parenchyma and requires targeted agents to cross the blood–brain barrier (BBB).3 CAA is present in a majority of people with AD (78–98%), and both are associated with the amyloid disposition and eventual neurological decline.4–6 Unfortunately, there are currently no effective prevention or treatment strategies for CAA. To date, a definitive diagnosis of CAA can only be made through a post-mortem examination of the brain; therefore, probes for the imaging of amyloid β are highly desirable. This led to the development of a variety of chemical scaffolds as Aβ-imaging tracers such as the thioflavin T analogues, chalcone, and curcumin derivatives that displayed high binding affinity toward Aβ aggregates.7–10

Multiple researchers have explored the development of positron emission tomography (PET) radiopharmaceuticals that target amyloid plaques. Pittsburgh compound B [11C]C-PiB (T1/2 = 20 min, β′ ≈ 100%, Emax = 0.96 MeV) is widely studied as the first agent to show increased retention in regions containing high levels of amyloid plaques.1,12 Several 18F-labeled PET tracers (T1/2 = 110 min, β′ ≈ 97%, Emax = 0.63 MeV) have also been investigated and have more potential for broader clinical applications due to their longer half-life. In fact, three 18F ligands have been approved for clinical use of imaging amyloid plaque density in patients by regulatory authorities in both Europe and the United States, including [18F]F-AV-45 (Florbetapir), [18F]F-BAY94–9172 (Florbetaben), and [18F]F-PiB (Flutemetamol).13–15 However, radiolabeling schemes of 11C and 18F complexes often require complex multistep synthesis and readily cross the BBB, which means they cannot distinguish between AD and CAA. The BBB serves to separate the brain’s blood vessels and components that make up brain tissues. Previous studies proposed that the selectivity of radiolabeled compounds for CAA stems from limited BBB penetration, thus restricting access to brain parenchyma where amyloid β is deposited for AD.16,17 Therefore, the design of novel radiopharmaceuticals that have more straightforward radiolabeling schemes such as the metal-based radionuclide 68Ga and have low BBB permeability would be desirable.

Compared to 11C and 18F, 68Ga (T1/2 = 68 min, β′ = 89%, Emax = 1.92 MeV) is a generator produced positron-emitting radionuclide, thus allowing for the distribution of PET imaging agents independent of on-site cyclotrons. The comparatively long half-life of the parent radionuclide (68Ge) of 271 days can provide 68Ga for an extended period of 6 months and multiple elutions can be performed in a day, resulting in 68Ga being a more cost-effective and reliable source of radionuclides.18

Received: April 15, 2022
Accepted: May 20, 2022
Published: June 6, 2022
Additionally, $^{68}$Ga has well-established coordination chemistry and fast and selective complex formation for direct labeling of biomolecules, thus making it an attractive option for amyloid β (Aβ) imaging.\textsuperscript{19}

Multiple gallium-based imaging agents have been proposed and tested in vitro and in vivo for the imaging of Aβ plaques. Zha et al. described a series of $^{68}$Ga-labeled styrylpyridine derivatives with $N,N'$-bis[2-hydroxy-5-(carboxyethyl)benzyl]-ethylenediamine-$N,N'$-dicarboxylic acid (HBED-CC) as the metal-
chelating agent, which exhibited excellent affinity toward amyloid β on post-mortem brain sections from patients diagnosed with AD.17 Watanabe et al. reported 68Ga-labeled benzofuran derivatives conjugated with metal-chelating 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid (DOTA), and fluorescence staining of Tg2576 mouse brain sections incubated in non-radioactive gallium complexes revealed clear staining of amyloid β plaques.20 Cressier et al. also introduced 68Ga-labeled PiB derivatives for the imaging of amyloid β plaques; however, in vitro autoradiography in human brain sections revealed their weak affinity for amyloid deposits.21 On the other hand, divalent binding has been reported to enhance binding affinity for Aβ aggregates.26

Here, we investigated a series of gallium-coordination bifunctional chelators (BFCs) with an Aβ-binding 2-(4-hydroxyphenyl)-benzothiazole moiety and metal-chelating 1,4,7-triazacyclononane (TACN) ligands (Figure 1). The TACN backbone was reported to efficiently chelate various metal ions including Cu(II), Ga(III), Sc(III), and In(III). A comparative study showed that TACN derivatives compete favorably for Ga(III) in reactions with HBED and DOTA.27 68Ga-labeled biomolecules with NOTA (a TACN derivative) are also superior in vivo in comparison to HBED and DOTA.28,29 In this study, multiple Aβ-binding moieties were generated on the N-atoms of TACN metal-binding fragments to increase the affinity of radiolabeled complexes to amyloid β.30–36 Multivalent binding has been reported to enhance binding affinity. Ikuni et al. have evaluated bivalent [99mTc]-Tc-Ham complexes and confirmed that bivalency led to superior binding affinity for amyloid β when compared to monovalent complexes.36 Cho et al. have recently proposed a series of divalent BFCs that showed enhanced binding affinity toward Aβ aggregates when comparing the autoradiographic images of 5xFAD mouse brain sections incubated with the mono- or divalent 64Cu complexes.30 This study evaluated novel TACN-based BFCs for CAA imaging by examining the radiochemistry with 68Ga, affinity toward amyloid β in 5xFAD mice brain sections, and biodistribution in normal CD-1 mice.

## RESULTS

### Design and Syntheses of BFCs.** YW-11 was synthesized as previously described.** The synthesis of the other compounds is outlined in Scheme S1. To further improve the binding affinity for amyloid β, multiple Aβ-binding fragments were conjugated to the TACN backbone, thus generating the bivalent YW-15 and trivalent YW-11 product, respectively. An additional carboxylate arm was present in the bivalent YW-18, which served to enhance the metal-chelating ability of this BFC. Characterization of these compounds was performed through ESI-MS and NMR (Figures S1–S12).

**Histological Staining of 5xFAD Mouse Brain Sections.** Figure 2 depicts the staining of 5xFAD brain sections with novel BFCs and sequentially Congo Red. Intense fluorescence signals were detected upon the incubation of 11-month-old 5xFAD mouse brain sections with BFC solution (left) and with Congo Red (middle). YW-13, YW-15, and YW-18 show fairly good colocalization of the two panels, as indicated by Pearson’s correlation coefficients of 0.53–0.73, suggesting that these BFCs exhibit good affinity for the amyloid aggregates.30–36 In contrast, YW-11 exhibits weak colocalization with the Congo Red-stained region (Pearson’s correlation coefficient = 0.2).

The specific Aβ binding of BFCs is further confirmed upon the incubation of 5xFAD mouse brain sections (11-month-old) with the AF594-HJ3.4 antibody (Figure 3). Fluorescence images show that the colocalization between YW-13 and YW-18 (left) and the HJ3.4 antibody (middle) is highly consistent with the Congo Red staining study. There is a slight improvement in the colocalization between YW-15 and the HJ3.4 antibody with Pearson’s correlation coefficients of 0.69 as compared to 0.53 for Congo Red staining.

**Radiolabeling of BFCs.** BFCs were radiolabeled with 68Ga at 95 °C for 15 min in NH4OAc buffer pH 5.5, resulting in products of high radiochemical yield and radiochemical purity (>95%), as illustrated by radio-high-pressure liquid chromatography (HPLC) except for YW-11 which is 90% pure (Figure S13). A single radiolabeled peak was observed for YW-13, YW-15, and YW-18 when complexed with 68Ga. In the case of YW-11, the complexed product contained two distinct radiolabeled peaks with the minor peak likely due to the loss of 65Ga when complexed with 68Ga. In the case of YW-11, the complexed product contained two distinct radiolabeled peaks with the major peak likely due to the loss of 65Ga when complexed with 68Ga.

**Lipophilicity Studies.** The logD<sub>oct</sub> values for radiotracers were determined using octanol–PBS partitioning as shown in Table 1. 68Ga-YW-18 has the highest logD<sub>oct</sub> value of 1.66 ± 0.05, followed by 68Ga-YW-11 of 1.58 ± 0.09.
In Vitro Autoradiography Studies. The brain sections of 5xFAD and WT mice (11-month-old) were utilized and stained with radioactive complexes (Figure 4). The autoradiographic images showed effective blocking after 5xFAD brain sections were incubated with excess 2-(4-hydroxyphenyl)benzothiazole, indicating that 68Ga-radiolabeled complexes were competing for the same amyloid-binding sites. Autoradiographic images revealed more intense signals in 5xFAD brain sections compared to those in WT ones when incubated with 68Ga-radiolabeled complexes, thus confirming the specific binding property of the BFCs to amyloid plaques. Interestingly, even the 68Ga complex of YW-11, which itself does not bind specifically to Aβ plaques, does exhibit specific binding, suggesting that the conformation and charge of the 68Ga complex lead to an improved binding to amyloid plaques. Compared to other BFCs, 68Ga-labeled bivalent complexes exhibited the highest non-specific binding as observed in WT brain sections. Quantitative data showed that 68GaGa-YW-11 had the highest intensity ratio of 5xFAD to WT brain sections of 4.0, compared to 2.9 for 68GaGa-YW-15, 3.0 for 68GaGa-YW-18, and 2.0 for 68GaGa-YW-13.

Biodistribution Studies. Experiments in vivo using CD-1 mice demonstrated low brain uptake after intravenous injection of 68Ga-radiolabeled complexes (Figure 5). The brain uptake of 68GaGa-YW-11 was 0.10 ± 0.03% ID/g at 2 min, reducing to 0.05 ± 0.02% ID/g at 2 h. The brain uptake of 68GaGa-YW-15 was 0.26 ± 0.12% ID/g at 2 min, slowly clearing to 0.07 ± 0.02% ID/g at 1 h and 0.03 ± 0.00% ID/g at 2 h. Compared to the other two, 68GaGa-YW-18 possessed the highest brain uptake at 2 min (0.33 ± 0.12% ID/g), which rapidly washed out to 0.01 ± 0.00% ID/g at 2 h. With regard to the brain-to-blood ratios, 68GaGa-YW-11 exhibited the lowest ratio at all time points (0.02–0.04) when compared to 68GaGa-YW-15 and 68GaGa-YW-18. Brain-to-blood ratios of 68GaGa-YW-15 and 68GaGa-YW-18 were comparable at 2 min (0.04 and 0.03, respectively), 1 h (0.07 and 0.08, respectively), and at 2 h (0.14 and 0.10, respectively). Table S1 shows the full biodistribution profiles of 68Ga-labeled radiotracers in CD-1 mice. High uptake was observed in the lung and liver for 68GaGa-YW-11, in which the radioactive uptake effectively cleared out from the lung and remained persistent in the liver at 2 h. 68GaGa-YW-15 also had high lung and liver uptake initially, and lung uptake rapidly cleared out, while liver...
uptake remained high at 2 h. [68Ga]Ga-YW-18 had the best non-target tissue clearance with the lung and liver uptake of less than 2% ID/g at 2 h.

## DISCUSSION

The present studies report a series of TACN-based BFCs radiolabeled with 68Ga as the potential PET imaging agent for amyloid β. The selective staining of the novel BFCs toward amyloid aggregates was investigated in vitro studies using 5xFAD mice. Intense fluorescence signals and good Pearson’s correlation coefficients with Congo Red or HJ3.4 antibody staining suggest that YW-13, YW-15, and YW-18 can bind to the amyloid β in the brain sections specifically. In our recent reports, we have shown that the free BFCs and the corresponding Cu(II) complexes show similar binding affinities and specificity for the amyloid plaques, as confirmed by both fluorescence microscopy and autoradiography. In addition, other studies have reported that different Aβ-binding chelators and their corresponding Ga(III) complexes exhibit similar binding affinities (within 3–8 fold) for Aβ aggregates. While ideally in vitro studies should be performed to clearly evaluate the effect of Ga chelation on the amyloid-binding affinity of newly developed chelators, we considered the previous results support our hypothesis that the designed BFCs and their Ga(III) complexes should exhibit similar amyloid-binding affinities, at least for the initial autoradiography and biodistribution studies described herein.

Radiolabeling with 68Ga was efficient, and a high radiochemical yield of 95% was achieved within 15 min of heating at 95 °C. Harsh conditions are standard for 68Ga labeling as often required to achieve rapid radiolabeling due to the short half-life of 68 min. However, heating at elevated temperature can have detrimental effects on larger biomolecules such as proteins, which is not the case for our studies. All 68Ga conjugates were subsequently used without further purification. The retention times in radio-HPLC correspond to the molecular weight of each product with YW-13 at 9:01 min, YW-15 at 10:40 min, and YW-18 at 11:01 min upon the addition of an extra amyloid-binding motif. YW-11 has two retention times—12:47 min that corresponds to the original trivalent radiolabeled complex and 10:41 min for the bivalent product after degradation. Ligand lipophilicity was assessed to predict non-specific binding due to increased hydrophobicity. In our studies, [68Ga]Ga-YW-13 has the lowest logDoct with only one amyloid-binding motif in the backbone. The addition of bulky substituents in the backbone resulted in increased hydrophobicity of the compound; thus, increased logDoct for bivalent and trivalent radiolabeled complexes were observed. This was confirmed in our studies that [68Ga]Ga-YW-11 has a higher logDoct compared to [68Ga]Ga-YW-15 likely due to the additional amyloid-binding motifs. On the other hand, [68Ga]Ga-YW-18 has a higher logDoct compared to [68Ga]Ga-YW-15 due to its complexation with 68Ga to form a neutral species.

Autoradiographic images confirmed the specific binding of 68Ga-radiolabeled complexes toward amyloid β. The intensity ratios of 5xFAD to WT brain section signals indicated that the introduction of extra amyloid β targeting moieties increased the affinity of BFCs to amyloid plaques, although the overall size and charge of the 68Ga-radiolabeled complexes can affect the amyloid-binding affinity. This corresponds to the previous studies that indicate the ability of multivalent ligands to enhance binding affinity. For example, a comparison study of 99mTc-hydroxamamide (99mTc-Ham) complexes with monovalent and bivalent amyloid ligand was performed, and autoradiography of Tg2576 APP transgenic mice showed a higher binding affinity for amyloid β of the bivalent complex. Another study by Cho et al. also confirmed the multivalent ligand effect on Aβ binding as presented in about 1.5-fold increase in average intensities of the 5xFAD brain sections after the treatment of mono- or divalent 64Cu complexes.

Biodistribution studies in normal CD-1 mice revealed low brain uptake of novel 68Ga-radiolabeled complexes in vivo. The low brain uptake of novel 68Ga-radiolabeled BFCs supports that they are suitable for the imaging of amyloid β on the walls of cerebral blood vessels, not those in the parenchymal brain tissues. Zha et al. have evaluated styrylpyridine derivatives radiolabeled with 68Ga for the imaging of amyloids in CAA that displayed specific binding toward Aβ plaques and had low brain uptake (0.1–0.3% ID/g at 2 min). Their reported brain uptake values were comparable to the brain uptake of [68Ga]Ga-YW-11 (0.10 ± 0.03% ID/g at 2 min), [68Ga]Ga-YW-15 (0.26 ± 0.12% ID/g at 2 min), and [68Ga]Ga-YW-18 (0.33 ± 0.12% ID/g at 2 min), thus highlighting the potential of novel radiotracers to selectively label amyloid β on the vessel walls.

## CONCLUSIONS

In conclusion, novel TACN complexes with multivalent amyloid-binding groups present useful molecular imaging probes for CAA due to their high binding affinity for Aβ plaques. Histological staining of 5xFAD mouse brain sections illustrated the specific binding of 68Ga bivalent complexes to amyloid β. In vitro autoradiography indicated the enhancement of the binding affinity by multivalency as reflected by the increased intensity ratios of 5xFAD brain sections compared to WT age-matched ones. The compounds exhibited low brain uptake in vivo which can be useful for the development of CAA-specific imaging agents to differentiate CAA from AD. Taken together, these findings strongly suggest that 68Ga bivalent complexes are good imaging probes targeting amyloid aggregates deposited in CAA and peripheral amyloidosis.

## EXPERIMENTAL SECTION

**General Methods.** All solvents and reagents used in this study were obtained from Sigma Aldrich (St. Louis, MO) or Fisher Scientific (Pittsburgh, PA). Buffers used for radiolabeling were prepared in chelexed Milli-Q water which was filtered through a 0.22 μm nylon filter. A Varian Mercury-300 spectrometer or a VARIAN UNITY Inova 400 spectrometer was utilized to record 1H (300 MHz) NMR spectra. A VARIAN VXR 500 with a UNITY INOVA Console spectrometer was used to record 13C (126 MHz) NMR spectra. Chemical shifts are reported in parts per million and referenced to residual solvent resonance peaks. Radio-TLC detection was accomplished using a Bioscan 200 imaging scanner (Bioscan, Inc., Washington, DC). Radioactive samples were counted on a Beckman Gamma 8000 counter containing a NaI crystal (Beckman Instruments, Inc., Irvine, CA). A two-solvent reversed-phase HPLC system was used to evaluate the radiolabeling efficiency with water [0.05% trifluoroacetic acid (TFA)] and acetonitrile (0.05% TFA). HPLC used a Kinetex (Phenomenex) C-18 column (5 μm, 4.6 × 150 mm I.D.). The HPLC instrument was composed of UV absorbance detectors set at 220 and 280 nm, a NaI radiotracer detector, and a
photodiode array detector. A gradient elution with acetonitrile (0.1% TFA) 0–100% buffer mobile phase over the course of 13 min and a 1 mL/min flow rate was developed for radiochemical purity profiling.

**Syntheses of BFCs. YW-11.** Paraformaldehyde (0.043 g, 1.4 mmol) was added to a solution of TACN (0.0875 g, 0.68 mmol) in 1,4-dioxane (15 mL), followed by heating under reflux for 1 h. 2-(4-Hydroxy-3-methoxy)-benzothiazole (0.32 g, 1.23 mmol) in EtOH (10 mL) was then added, followed by an additional 36 h of reflux. The resulting mixture was cooled to room temperature. After the removal of the solvent, an orange-yellow residue was collected. This residue was purified by flash column chromatography using DCM/MeOH (30:1). The resulting yellow solution was dried and a yellow precipitate formed (71 mg, yield 4%).1H NMR (300 MHz, CDCl3) δ 8.0 (d, J = 8.1 Hz, 2H), 7.8 (d, J = 7.9 Hz, 3H), 7.6 (s, 3H), 7.4 (t, J = 7.7 Hz, 3H), 7.3 (dd, J = 14.2, 6.2 Hz, 6H), 4.0 (s, 9H), 3.9 (s, 6H), 3.0 (s, 12H). 13C NMR (126 MHz, CDCl3) δ 168.6, 153.5, 148.4, 148.0, 134.8, 130.6, 126.5, 124.9, 123.3, 121.9, 110.3, 56.4, 30.0. ESI-MS: calcd for [M + H]+, 782.3001; found, 782.2833.

YW-13. The synthesis of YW-13 was conducted as previously described.35

YW-15. Paraformaldehyde (0.067 g, 2.2 mmol) was added to a solution of TACN (0.106 g, 0.82 mmol) in EtOH (10 mL), followed by heating under reflux for 1 h. 2-(4-Hydroxy-3-methoxy)-benzothiazole (0.32 g, 1.23 mmol) in EtOH (10 mL) was then added, followed by an additional 36 h of reflux, and then the resulting mixture was cooled to room temperature. After the removal of the solvent, an orange-yellow residue was collected. This residue was purified to give a yellow solution by Combi-Flash (reverse-phase) using MeCN/H2O/TFA (60:40:0.1), followed by the neutralization process with NaHCO3 and extraction with dichloromethane. The resulting solution was then dried and a yellow solid formed (21 mg, yield 4%).1H NMR (400 MHz, CDCl3) δ 8.0 (d, J = 8.1 Hz, 2H), 7.8 (d, J = 7.9 Hz, 2H), 7.6 (s, 2H), 7.4 (t, J = 7.7 Hz, 2H), 7.4 (s, 2H), 7.3 (t, J = 7.6 Hz, 2H), 4.0 (s, 6H), 3.8 (s, 4H), 3.1–2.7 (m, 11H). 13C NMR (126 MHz, CDCl3) δ 154.4, 148.5, 135.0, 126.4, 124.9, 124.3, 124.1, 122.9, 122.2, 121.7, 109.9, 56.4, 53.7. HR-ESI-MS: calcd for [M + H]+, 668.2321; found, 668.2370.

YW-16. tert-Butyl bromoacetate (33.5 mg, 0.17 mmol) in 5 mL of MeCN was added to a suspension of YW-15 (95.6 mg, 0.14 mmol) and sodium carbonate (18 mg, 0.17 mmol) in 15 mL of 1:1 (v/v) MeCN/DCM, followed by stirring of the reaction mixture for 20 h at room temperature. After the removal of the solvent, an orange-yellow residue was collected. This residue was purified to give a yellow solution by Combi-Flash (reverse-phase) using MeCN/H2O/TFA (60:40:0.1), followed by the neutralization process with NaHCO3 and extraction with dichloromethane. The resulting solution was then dried and a yellow solid formed (76 mg, yield 68%).1H NMR (300 MHz, CDCl3) δ 8.0 (d, J = 8.1 Hz, 2H), 7.9 (d, J = 7.8 Hz, 2H), 7.7 (s, 2H), 7.5–7.4 (m, 4H), 7.4 (t, J = 7.6 Hz, 2H), 4.2 (d, J = 2.5 Hz, 4H), 3.8 (s, 6H), 3.2 (d, J = 8.2 Hz, 1H), 1.3 (s, 9H). 13C NMR (126 MHz, CDCl3) δ 171.0, 154.1, 148.5, 134.9, 126.5, 124.9, 122.8, 121.8, 110.2, 81.4, 56.4, 28.4, 28.0. HR-ESI-MS: calcd for [M + H]+, 726.2375; found, 726.2370.

YW-18. A reaction mixture of YW-16 (76 mg, 0.10 mmol) and 5 mL of 6 M hydrochloric acid was stirred and refluxed for 18 h. After the removal of the solvent, a yellow residue was collected. This residue was purified to give a yellow solution by Combi-Flash (reverse-phase) using MeCN/H2O/TFA (50:50:0.1), followed by the neutralization process with NaHCO3 and extraction with dichloromethane. The resulting solution was then dried and a yellow solid formed (19.4 mg, yield 28%).1H NMR (499 MHz, CD3OD) δ 7.9 (d, J = 8.1 Hz, 2H), 7.8 (d, J = 7.9 Hz, 2H), 7.6 (s, 2H), 7.5 (s, 2H), 7.4 (t, J = 7.6 Hz, 2H), 7.3 (t, J = 7.5 Hz, 2H), 4.1 (s, 4H), 3.8 (d, J = 3.6 Hz, 7H), 3.4 (d, J = 2.5 Hz, 2H), 3.3 (d, J = 2.0 Hz, 15H).13C NMR (126 MHz, CD3OD) δ 168.6, 153.5, 148.4, 134.5, 126.6, 125.3, 125.3, 122.8, 121.1, 121.7, 110.3, 55.6, 54.0, 50.7. HR-ESI-MS: calcd for [M + H]+, 726.2375; found, 726.2422.

**Histological Staining of 5xFAD Mouse Brain Sections.** 5xFAD mouse brain sections (11-month-old) were used to evaluate the binding affinity for amyloid aggregates. The sections were blocked for 10 min with bovine serum albumin (2% BSA in PBS, pH 7.4), followed by 30 min incubation with BFCs dissolved in PBS. The sections were subsequently stained for 30 min in a 2 μM Congo Red solution. Brain sections were incubated for 4 min with BSA, rinsed three times with PBS (each cycle 2 min) followed by 2 min DI water wash, and then mounted with non-fluorescent mounting media in order to remove non-specific binding. To further confirm the specificity of novel BFCs toward amyloid β, the AF594-conjugated anti-Ab antibody (AF594-HJ3.4 antibody) solution (1 μg/mL) was added to mouse brain sections (11-month-old) for 1 h at room temperature, followed by the same incubation and wash steps as previously described for Congo Red staining. The antibodies were labeled with dye Cy594 via the Mix-n-Stain CF 594 Antibody Labeling Kit (Sigma Aldrich). A Zeiss LSM 7010 confocal fluorescent microscope and an InVitrogen EVOS FL Auto 2 Imaging System (Thermo Fisher, USA) were used to image stained brain sections. Colocalization analysis and determination of the Pearson’s correlation coefficient were performed using ImageJ (1.52, public domain) software.

**Radionuclide Production.** 68Ga was produced using a commercial 68Ge/68Ga generator (Eckert & Ziegler, Berlin, Germany) system as described.37 Briefly, the elution of 68Ga from the generator was carried out in 5 mL of 0.1 M HCl. The eluted activity was added to a Strata XC strong cation exchange column 30 mg/mL 33 μm (Phenomenex, Torrance, CA) which effectively retains the activity. 0.8 mL of 98% acetone (0.02 M HCl) was added to the column, and the eluent was collected in a 1.5 mL Eppendorf tube, followed by heating at 95 °C for 15 min until 10–20 μL 68Ga was achieved.

**Radiolabeling of BFCs.** Efficient labeling with 68Ga was accomplished by adding 20 μL of 1 mM ligand in DMSO to 7.4 MBq (200 μCi) of 68Ga in 50 μL of 0.1 M NH4OAc (pH 5.5) at 95 °C for 15 min. Radiolabeled products were evaluated using HPLC. A gradient from 0 to 100% and acetone (0.1% TFA) was used with a flow rate of 1 mL/min in 13 min.

**Lipophilicity Studies.** An equal volume of n-octanol and PBS 1X was added to 10 Eppendorf tubes (500 μL each). An aliquot of 5–10 μL radiolabeled 68Ga complexes was added to each tube, vortexed, and incubated for 1 h at room temperature with moderate shaking. The mixtures were then allowed to sit still in the bunker for 30 min for the two layers—aqueous and n-octanol to separate. 100 μL from each layer was collected in tubes, and the radioactivity was counted using an automated gamma counter. The counts (in cpm) were corrected for radioactive decay. logDaw was calculated to be the logarithm of the ratio of (radioactivity of the organic phase)/(radioactivity of the aqueous phase). The average of 10
replicate values was recorded as the logD_{oct} for each compound.

In Vitro Autoradiography Studies. Brain sections of SxFAD transgenic mice and WT mice (11-month-old) were immersed in a cryo-protectant solution. Brain sections were rinsed three times with 100% PBS, and each section was placed in each well of the 12-well plate. 3.7 MBq (100 μCi) 68Ga-labeled compounds in 1 mL of PBS were added to the wells, and the well plates were incubated at room temperature for 1 h. Specific binding of 68Ga-labeled BFCs toward amyloid plaques was evaluated in blocking studies by co-incubating with excess 2-(4-hydroxyphenyl)-benzothiazole. Brain sections were then rinsed 3 × 2 min in ice-cold PBS before being removed. Sections were placed on glass microscope slides and completely air-dried at room temperature. The slides were placed in an imaging cassette in contact with a phosphor-imaging screen plate (GE Healthcare Life Sciences). The screen was exposed overnight at −20 °C and then scanned on a phosphor-imager plate scanner (Storm 840). ImageJ (1.53, public domain) software was used to review the images.

Biodistribution Studies. All animals involved were obtained from Charles River Laboratories (Wilmington, MA). For animal research, the Guidelines for Care and Use of Research Animals established by the Animal Studies Committee of Washington University School of Medicine and the Division of Comparative Medicine were strictly followed. CD-1 female mice (5–7 weeks of age) were intravenously injected with 10 μCi (0.37 MBq) of 68Ga-radiotracers in 100 μL of saline. Mice were sacrificed after a period of 2, 60, and 240 min after intravenous injection. Organs of interest (blood, lung, liver, kidney, muscle, brain, bone, and tail) were harvested and counted on a gamma counter. Radioactivity concentrations were decay-corrected and expressed as percent injected dose per gram (%ID/g).

Statistical Analysis. All values are expressed as mean ± SD. Quantitative data were analyzed using Prism software version 9 (GraphPad Software, La Jolla, CA). One-way analysis of variance and Student’s t-test are statistical methods used in the study, in which a p-value of 0.05 or lower is considered statistically significant.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/10.1021/acsomega.2c02369.

Characterization of novel BFCs using 1H NMR, 13C NMR, and HR ESI-MS; HPLC chromatograms showing the 68Ga-labeled radiotracer; and biodistribution profile of 68Ga-labeled radiotracers in CD-1 mice (PDF)

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Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the NIH (R01GM114588 to L.M.M.). We thank Nikki Fettig and Lori Strong from the Washington University Small Animal imaging facility for providing technical assistance for animal studies.

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