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¹⁸F-Labeled pyrido[3,4-*d*]pyrimidine as an effective probe for imaging of L858R-mutant epidermal growth factor receptor

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ABSTRACT: In non-small-cell lung carcinoma patients, L858R mutation of epidermal growth factor receptor (EGFR) is often found, and molecular target therapy using EGFR tyrosine kinase inhibitors is effective for the patients. However, the treatment frequently develops drug resistance by secondary mutation, of which approximately 50% is T790M mutation. Therefore, the ability to predict whether EGFR will undergo secondary mutation is extremely important. We synthesized a novel radiofluorinated 4-(anilino)pyrido[3,4-*d*]pyrimidine derivative (¹⁸F]APP-1) and evaluated its potential as a positron emission tomography (PET) imaging probe to discriminate the difference in mutations of tumors. EGFR inhibition assay, cell-uptake, and biodistribution study showed that [¹⁸F]APP-1 binds specifically to the L858R mutant EGFR but not to the L858R/T790M mutant. Finally, on PET imaging study using [¹⁸F]APP-1 with tumor-bearing mice, the H3255 tumor (L858R mutant) was more clearly visualized than the H1975 tumor (L858R/T790M mutant).

Non-small-cell lung carcinoma (NSCLC) is a class of lung cancer that accounts for 80% of lung cancer cases and is a major cause of cancer-related deaths. In approximately 10%–30% of patients with NSCLC, a somatic activating mutation occurs in the tyrosine kinase (TK) domain of the epidermal growth factor receptor (EGFR) and causes the exon 21 mutation, resulting in leucine being replaced by arginine at position 858 (L858R mutant) or exon 19 deletions in the EGFR gene.¹ The increased kinase activity of mutant EGFR plays a key role in cell proliferation and angiogenesis in cancer cells. Therefore, EGFR-TK inhibitors (EGFR-TKIs), such as gefitinib (Iressa[®]), erlotinib (Tarceva[®]), and afatinib (Giotrif[®]), are used in NSCLC therapy to bind to the ATP domain in mutant EGFR-TK.²

However, patients who initially respond to EGFR-TKIs typically develop drug resistance within 6–12 months after the start of therapy, thereby inevitably disrupting the therapy.³ The most common factor is the occurrence of secondary mutation of the mutant EGFR gene, which leads to methionine replacing threonine at position 790 of EGFR (T790M mutation). The T790M mutation occurs in approximately 50% of patients with resistance to EGFR-TKIs.^{3,4} Therefore, predicting whether EGFR undergoes this secondary mutation is extremely important for planning the treatment of EGFR-TKIs. For clinical settings, genetic testing is conducted via biopsy to find muta-

tions and provide a definitive cancer diagnosis before starting the therapy.⁵ However, because of the invasiveness of this procedure, such testing is done only when the effect of molecular targeting drugs decreases over the course of treatment. Therefore, developing noninvasive diagnostics techniques that can determine the therapeutic efficiency of EGFR-TKIs has become necessary.

Positron emission tomography (PET) is a molecular imaging technique that enables noninvasive detection of specific molecules in living systems, and is expected, in particular, to detect the presence of mutant EGFR. Furthermore, some radiolabeled EGFR-TKIs, including [¹⁸F]gefitinib, [¹⁸F]afatinib and [¹¹C]erlotinib, have been investigated using PET probes for EGFR-TK-positive tumor imaging.^{6–12} However, the use of these compounds does not permit visualization of an EGFR-TK-positive tumor. In addition, the use of [¹¹C]erlotinib reportedly allows primary and secondary mutant tumors to be differentiated by visualizing the former but not the latter,¹² and it leads to unclear images of L858R mutant tumors, similar to the results for other radiolabeled EGFR-TKIs.

Previous investigations of a series of 4-(anilino)pyrido[3,4-*d*]pyrimidine derivatives as EGFR-TKIs claim that these compounds show lower half-maximal inhibitory concentration (IC₅₀) to EGFR-TK compared with 4-(anilino)quinazoline.^{13–15} Therefore, the radiolabeled 4-(anilino)pyrido[3,4-*d*]pyrimidine

derivative is also expected to become an imaging-probe candidate for tumors targeted by EGFR-TKIs. In addition, we aimed drug design on the grounds that incorporating a Michael acceptor unit at position 6 of pyrido[3,4-*d*]pyrimidine and quinazoline scaffolds leads to irreversible inhibition of EGFR-TK through a covalent modification of cysteine 797 in the ATP binding domain¹⁶⁻¹⁸ and that the piperazinyl group is useful to afford suitable water solubility and induce the radio-labeling site. Moreover, if the accumulation of the derivative differs between the primary and secondary mutant tumor, we hope to use 4-(anilino)pyrido[3,4-*d*]pyrimidine as an imaging probe to identify whether EGFR mutations are present. In the present study, we synthesize a novel radiofluorinated 4-(anilino)pyrido[3,4-*d*]pyrimidine derivative APP-1 (Figure 1) and evaluate its ability to discriminate between primary and secondary mutations in *in vitro* and *in vivo* experiments.

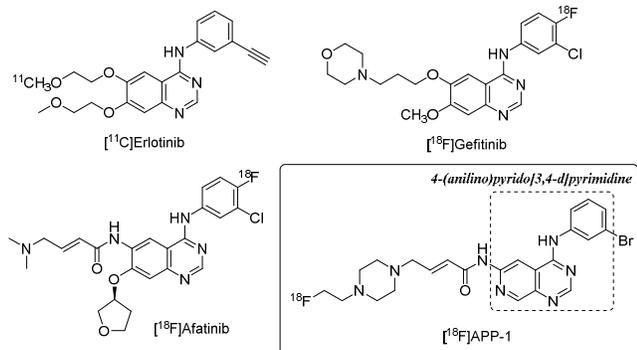
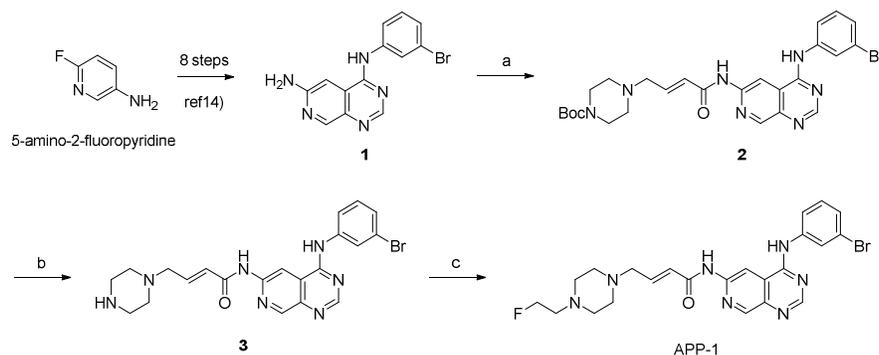


Figure 1. Chemical structure of EGFR-targeting PET imaging probes.

The nonradioactive APP-1 was synthesized as indicated in Scheme 1. First, 6-aminopyrido[3,4-*d*]pyrimidine **1** was prepared from 2-fluoro-5-aminopyridine via the synthetic route reported by Rewcastle et al.¹⁴ Compound **1** was coupled with 4-bromocrotonic acid by using 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride as the condensing agent followed by the addition of 1-(*tert*-butyloxycarbonyl)piperazine to obtain amide **2** at an 91% yield. The deprotection of the *tert*-butyloxycarbonyl group of compound **2** gave amine **3**. Finally, compound **3** was reacted with 2-fluoroethyl tosylate to obtain APP-1.

Scheme 1. Synthesis of nonradioactive APP-1 and its precursor **3**.



Reagents and conditions: (a) 4-bromocrotonic acid, 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride, DIPEA, DMF, rt, 1 h followed by 1-(*tert*-butyloxycarbonyl)piperazine, rt, 30 min, 91%; (b) TFA, dichloromethane, rt, 85%; (c) 2-fluoroethyl tosylate, Et₃N, DMF, rt, 45%.

The inhibition assay of APP-1 involved using erlotinib and AZD9291 to inhibit the L858R mutant and L858R/T790M mutant EGFR-TK; the results for IC₅₀ appear in Table 1. Erlotinib inhibits the L858R mutant EGFR kinase but not the L858R/T790M mutant,¹² and AZD9291 (osimertinib, Tagrisso[®]), developed by AstraZeneca to inhibit the L858R/T790M mutant EGFR-TK and recently approved by the US Food and Drug Administration, inhibits both the L858R and L858R/T790M mutants of EGFR-TK.¹⁹ As a result, both APP-1 and erlotinib inhibit L858R mutant EGFR-TK somewhat more than L858R/T790M mutant of EGFR-TK (15.6 ± 0.8 nM vs 326 ± 64 nM and 12.5 ± 6.0 nM vs 4040 ± 1270 nM, respectively), and AZD9291 potently inhibits mutant EGFR-TK (12.3 ± 3.1 nM vs 14.5 ± 5.3 nM). Thus, radioactive APP-1 is also expected to become a probe candidate for imaging EGFR-TK-positive tumors. In addition, APP-1 is found to be selective, although the range of selectivity is smaller than that of erlotinib. However, whether its selectivity suffices to visually discriminate between L858R- and L858R/T790M-mutant tumors remains to be determined. Therefore, we continue evaluating the potential of APP-1 for use in PET imaging.

Table 1. IC₅₀ for APP-1, erlotinib, and AZD9291.

Compound	IC ₅₀ (nM)	
	L858R	L858R/T790M
APP-1	15.6 ± 0.8	326 ± 64
Erlotinib	12.5 ± 6.0	4040 ± 1270
AZD9291	12.3 ± 3.1	14.5 ± 5.3

The values represent the mean ± SE (*n* = 3).

We synthesized ¹⁸F-labeled [¹⁸F]APP-1 from precursor **3** in a two-step reaction. First, we prepared radioactive 2-[¹⁸F]fluoroethyl tosylate by a nucleophilic displacement reaction of ethyleneglycol-1,2-ditosylate with the [¹⁸F]fluoride anion. After purification by preparative high-performance liquid chromatography (HPLC) and solid-phase extraction, 2-[¹⁸F]fluoroethyl tosylate was reacted with compound **3** for 20 min at 110°C to yield [¹⁸F]APP-1 in a radiochemical yield of 3.2 ± 0.94% [*n* = 5, end of synthesis (EOS), from potassium [¹⁸F]fluoride] after preparative HPLC. The total operation took less than 110 min. The isolated [¹⁸F]APP-1 was identified by a HPLC analysis with co-injection of APP-1 (Figure 2). The radiochemical purity and the specific activity exceeded 95% and 40.4 GBq/μmol, respectively.

post-injection, 3.80% ID/g at 3 h post-injection). Because the accumulation of [^{11}C]erlotinib for 1 h in H3255 tumors is reported to be decreasing over time,⁹ we assume that [^{18}F]APP-1 strongly binds to EGFR-TK in H3255 tumors by irreversible binding associated with a covalent bond via the Michael acceptor group. However, the slow clearance from normal tissue must be improved. At each time point, Table 2 also gives the tumor-to-blood, tumor-to-muscle, and tumor-to-lung ratios. All ratios increase over time and exceed three at 3 h post-injection. Therefore, we expect the use of [^{18}F]APP-1 for visualization of H3255 tumors in mice.

Furthermore, we studied *in vivo* blocking to determine the ability of [^{18}F] to discriminate between L858R and L858R/T790M mutant EGFRs (Figure 4). Co-administration of excess AZD9291 significantly reduced the accumulation of [^{18}F]APP-1 in H3255 tumors (54% inhibition) at 3 h post-injection. However, accumulation in H1975 tumors was not blocked by excess AZD9291. These results correspond to

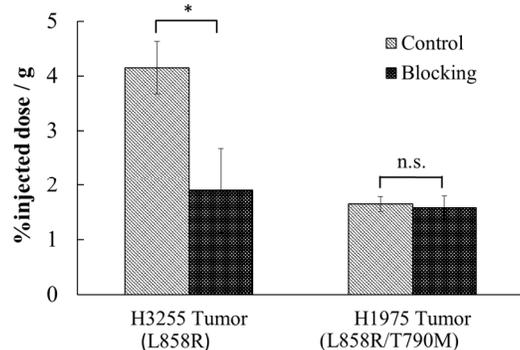


Figure 4. Effect of co-administration of AZD9291 on biodistribution of [^{18}F]APP-1 (3 h post-injection). The graphs show the mean %ID/g of four mice with the error bars giving the standard deviation (* $P < 0.01$).

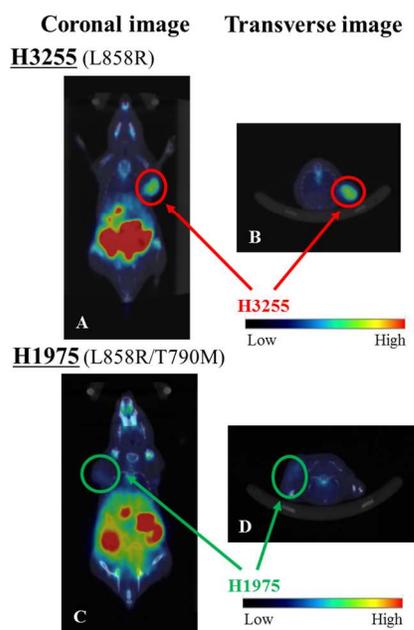


Figure 5. PET-CT image of [^{18}F]APP-1 in H3255- [(A), (B)] or in H1975- [(C), (D)] tumor-bearing mice at 3 h post-injection. Panels (A) and (C) show coronal images, while panels (B) and (D) show transverse images.

Table 3. Ratios of accumulated radioactivity in H3255 and H1975 tumor-bearing mice after PET-CT imaging.

Tumor	Ratio		
	Tumor/Blood	Tumor/Muscle	Tumor/Lung
H3255	3.12	6.80	3.25
H1975	0.74	2.95	0.74

those of the cell-uptake study (Figure 3). In other words, these results confirm that, in mice with mutant-EGFR-TK tumors, [^{18}F]APP-1 binds specifically to L858R mutant EGFR-TK but not to L858R/T790M mutant EGFR-TK.

Furthermore, we performed PET imaging of [^{18}F]APP-1 in H3255- or H1975-tumor-bearing mice (Figure 5). The images at 3 h post-injection of [^{18}F]APP-1 show that H3255 tumors are more clearly visualized than H1975 tumors. In addition, we measured the radioactivity in each organ and tissue after image acquisition and calculated the tumor-to-blood, tumor-to-muscle, and tumor-to-lung ratios (Table 3). The contrast between H3255 tumors and surrounding tissue is higher than that when using [^{11}C]erlotinib.¹³ These results suggest that [^{18}F]APP-1 is effective as an imaging probe that targets L858R mutant EGFR.

We designed and synthesized a radiofluorinated 4-(anilino)pyrido[3,4-*d*]pyrimidine derivative, APP-1, as a PET imaging agent to discriminate between L858R and L858R/T790M mutant EGFRs. When used in an EGFR-TK inhibition assay, APP-1 was the strongest inhibitor of the L858R mutant EGFR-TK, and a weak inhibitor of the L858R/T790M mutant EGFR-TK. The cell-uptake study shows that [^{18}F]APP-1 binds specifically to the L858R mutant EGFR-TK but not to the L858R/T790M mutant. Further assessment of the biodistribution revealed that [^{18}F]APP-1 results in a high tumor-to-tissue ratio in H3255-tumor-bearing mice, while co-injection of AZD9291 suggests that the accumulation of [^{18}F]APP-1 in tumors is specific to EGFR-TK. In addition, for PET imaging, the H3255 tumor is more clearly visualized than the H1975 tumor. Based on these results, we conclude that [^{18}F]APP-1 has a potential to be used as a PET imaging probe to discriminate between L858R and L858R/T790M mutant EGFRs in NSCLC.

ASSOCIATED CONTENT

Supporting Information

Full experimental procedures and characterization data for all new compounds described in this study. The Supporting Information is available free of charge on the ACS Publications website at DOI:XXX. (PDF)

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Author Contributions

The manuscript was written through contributions of all authors, and all the authors approve the final version of the manuscript. ‡These authors have contributed equally.

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Notes

The authors declare no competing financial interest.

ABBREVIATIONS

ATP, adenosine triphosphate; DIPEA, *N,N*-diisopropylethylamine; Boc, *tert*-butyloxycarbonyl; DMF, *N,N*-dimethylformamide; EGFR, epidermal growth factor receptor; EGFR-TK, epidermal growth factor receptor tyrosine kinase; EGFR-TKIs, epidermal growth factor receptor tyrosine kinase inhibitors; ID, injected dose; MeCN, acetonitrile; NSCLC, non-small-cell lung carcinoma; PET, positron emission tomography; HPLC, high-performance liquid chromatography; rt, room temperature; TFA, trifluoroacetic acid.

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