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[^{18}F]ZCDD083: A PFKFB3-Targeted PET Tracer for Atherosclerotic Plaque Imaging

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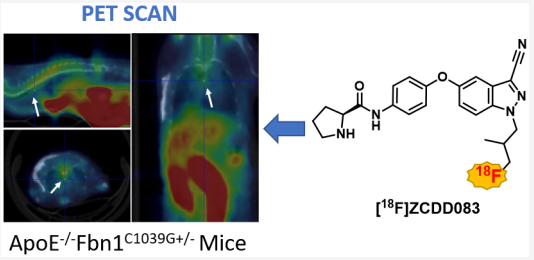
ABSTRACT: PFKFB3, a glycolysis-related enzyme upregulated in inflammatory conditions and angiogenesis, is an emerging target for diagnosis and therapy of atherosclerosis. The fluorinated phenoxindazole [^{18}F]**ZCDD083** was synthesized, radiolabeled in 17 ± 5% radiochemical yield and >99% radiochemical purity, and formulated for preclinical PET/CT imaging in mice. *In vivo* stability analysis showed no significant metabolite formation. Biodistribution studies showed high blood pool activity and slow hepatobiliary clearance. Significant activity was detected in the lung 2 h postinjection (pi) (11.0 ± 1.5%ID/g), while at 6 h pi no pulmonary background was observed. *Ex vivo* autoradiography at 6 h pi showed significant high uptake of [^{18}F]**ZCDD083** in the arch region and brachiocephalic artery of atherosclerotic mice, and no uptake in control mice, matching plaques distribution seen by lipid staining along with PFKFB3 expression seen by immunofluorescent staining. *In vivo* PET scans showed higher aortic region uptake of [^{18}F]**ZCDD083** in atherosclerotic ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ than in control mice (0.78 ± 0.05 vs 0.44 ± 0.09%ID/g). [^{18}F]**ZCDD083** was detected in aortic arch and brachiocephalic artery of ApoE$^{-/-}$ (with moderate atherosclerosis) and ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ (with severe, advanced atherosclerosis) mice, suggesting this tracer may be useful for the noninvasive detection of atherosclerotic plaques *in vivo*.



KEYWORDS: *Atherosclerosis, plaque, fluorine, PET imaging, glycolysis, preclinical*

Atherosclerosis is a pathological process characterized by progressive accumulation of lipids, inflammatory cells, and connective tissue in the arterial wall.[1] This process, leading to the formation of the so-called "atherosclerotic plaques", is predominantly asymptomatic. However, the progression of the disease can cause progressive stenosis of arterial lumen, which can eventually result in ischemic heart pain. Acute clinical events, such as myocardial infarction, stroke, and unstable angina, are mainly associated with instability of plaques and formation of occlusive thrombi.[2]

The progression of atherosclerotic plaques is initially asymptomatic, characterized by the slow growth of "silent" stable plaques. However, plaque rupture is associated with unstable angina, acute myocardial infarction, and sudden cardiac death. Similarly, rupture of carotid artery plaque is associated with cerebral ischemic events.[3] The risk of thrombotic complications of atherosclerosis is mostly related to the instability of an atheroma rather than the size of the plaque.

Currently, cardiovascular medicine aims principally to identify atherosclerotic plaques prone to rupture, improve the risk stratification, monitor the disease progression, assess new antiatherosclerotic therapies and promptly evaluate the efficacy of therapeutic treatment. PET imaging is noninvasive and has a great potential in this context, but there is a clear need for new targets and radiotracers for imaging unstable atherosclerotic plaque.[4,5]

The PFKFB3 enzyme is emerging as a new target for the *in vivo* assessment of atherosclerotic plaques.[6,7] PFKFB3 is a glycolysis-related enzyme upregulated in inflammatory and hypoxic conditions.[8,9] Several studies have shown a correlation between PFKFB3 and angiogenesis, which is a feature of vulnerable atherosclerotic plaques.[10−13] Here we describe the development of the ^{18}F-radiolabeled phenoxindazole compound **ZCDD083** as a PFKFB3-targeted PET radiotracer for imaging the atherosclerotic plaque *in vivo*.[14] **ZCDD083** is a close structural mimic of the potent inhibitor AZ68 (IC_{50}= 4 nM), whose radiofluorination was deemed to be chemically viable and unlikely to affect the binding to PFKFB3.

■ RESULTS

Phenol intermediate **2** (Scheme 1) was synthesized from *N*-Boc-proline and *O*-Bn-4-aminophenol, which were coupled to

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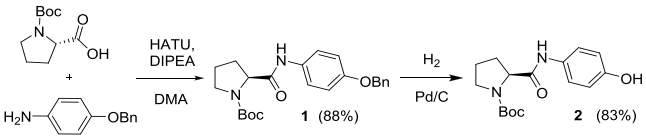
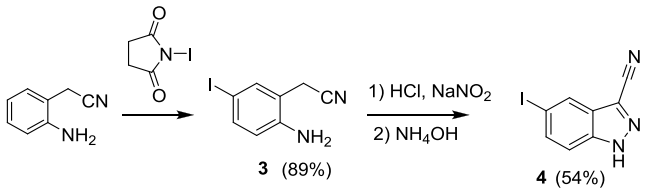
afford compound **1** that was debenzylated by hydrogenation over Pd/C.

Scheme 1. Synthesis of Phenol Intermediate 2



Indazole **4** (Scheme 2) was synthesized by NIS-promoted iodination of (2-amino)phenyl-acetonitrile, followed by

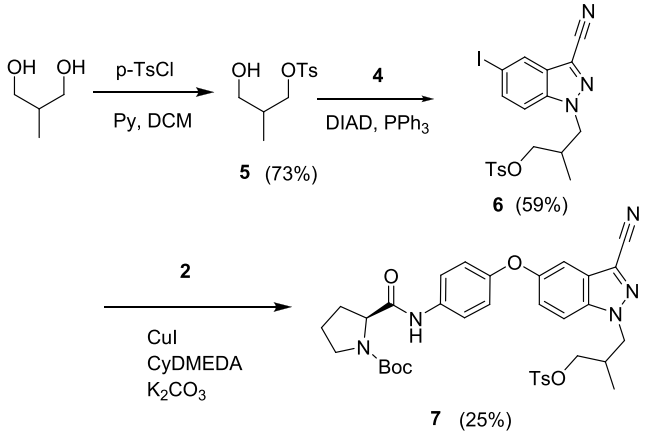
Scheme 2. Synthesis of Indazole 4



indazole ring formation via Sandmeyer reaction and intramolecular ring closure of the diazonium salt formed from **3**.

The radiofluorination precursor **7** (Scheme 3) was synthesized next. Commercial 2-methyl-1,3-propanediol was

Scheme 3. Synthesis of Radiofluorination Precursor 7



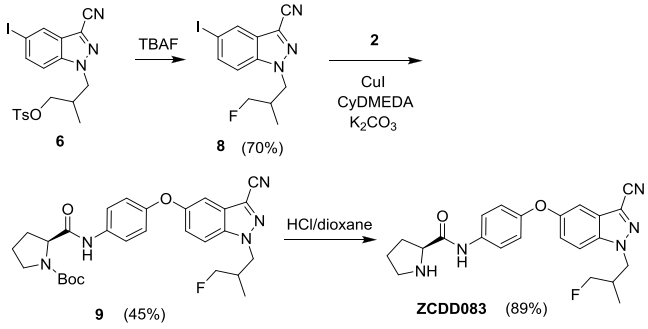
treated with tosyl chloride to give the mono tosylated derivative **5**, which was reacted with the indazole **4** via Mitsunobu reaction to give compound **6**. Ullmann-type coupling with phenol **2** afforded the target tosylated precursor **7**.

The "cold" (e.g., nonradioactive) tracer **ZCDD083** (Scheme 4) was prepared from the indazole tosylate **6**, which was treated with TBAF to give the fluorinated compound **8**. The latter was subjected to the Ullmann coupling with **2** affording **9**, which was *N*-Boc-deprotected to afford the target molecule.

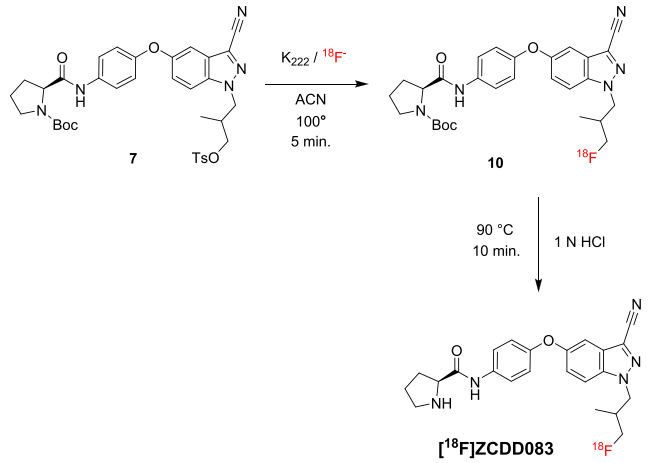
Starting from the tosylated precursor **7**, [^{18}F]**ZCDD083** was radiosynthesized in a two-step synthesis (Scheme 5) using standard ^{18}F-fluoride chemistry, producing first the protected tracer **10** which was then treated with HCl in order to remove the N-Boc-protection.

[^{18}F]**ZCDD083** was obtained with a 17 ± 5% radiochemical yield (decay-corrected to EOB), and the activity was in the range of 4.7−7.2 GBq (n = 7). The average time taken for

Scheme 4. Synthesis of "Cold" ZCDD083



Scheme 5. Radiosynthesis of [^{18}F]ZCDD083



synthesis, purification, and formulation was 65 min. [^{18}F]**ZCDD083** was obtained with radiochemical purity >99% and specific activity >130 GBq/μmol; no impurities were detected in the UV chromatogram (Figure 1) and no residual solvents other than ethanol (<10%) were detected (see Figure S4, Supporting Information).

A preliminary metabolite study was performed in healthy C57BL/6J mice (6 weeks old, female) to evaluate the *in vivo* plasma stability of [^{18}F]**ZCDD083**. The radio-HPLC analysis showed no significant metabolite formation within 6 h. The eluate from HPLC was collected in fractions and the radioactivity in each fraction was measured in a γ-counter. At

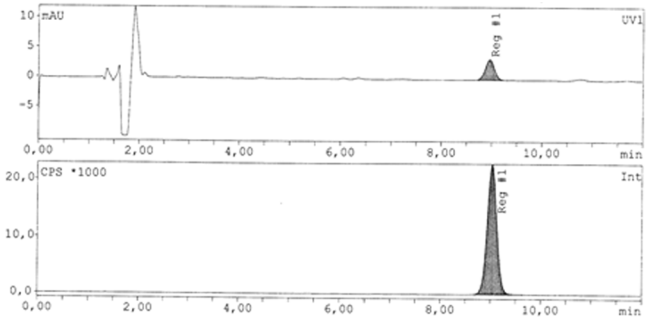


Figure 1. Chemical and radiochemical purity of [^{18}F]**ZCDD083** assessed by analytical RP-HPLC. No impurities were detected in the UV (top) and radioactive (bottom) chromatograms. Column: Phenomenex Luna C18 column (5 μm, 100 Å, 250 × 4.6 mm). Mobile phase: solvent A = H_2O + 0.1% TFA, solvent B = CH_3CN + 0.1% TFA; Isocratic method 40% B.

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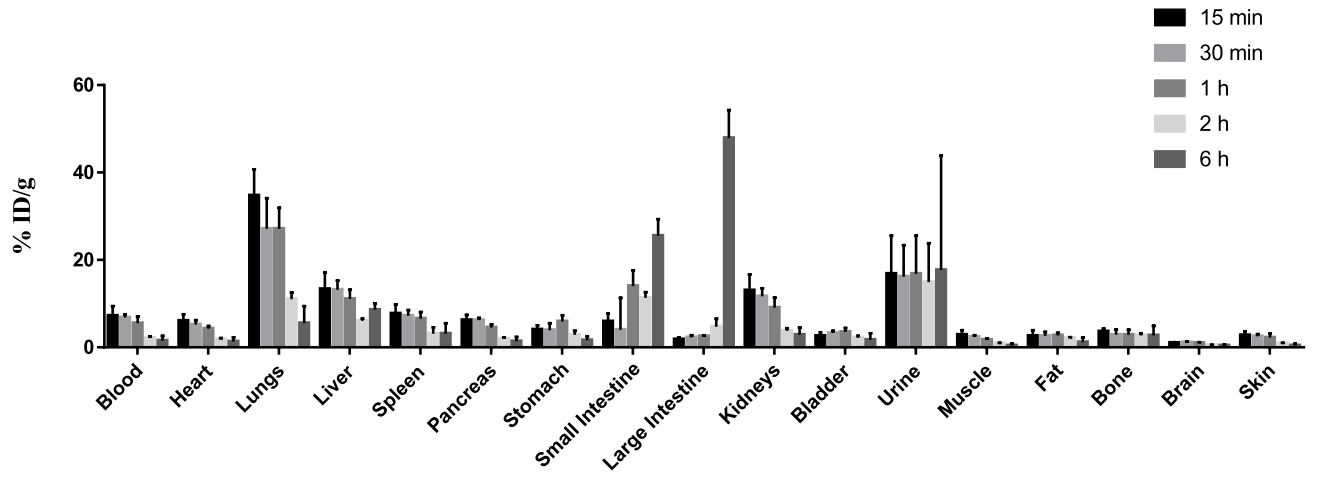

Figure 2. Ex vivo biodistribution of [^{18}F]**ZCDD083**. Slow blood clearance and high tracer uptake in the lungs were observed at earlier time points within 2 h pi. At 6 h pi [^{18}F]**ZCDD083** was mostly accumulated in the intestines.

6 h pi, 78.9% ± 1.2 of [^{18}F]**ZCDD083** was intact (see Table S1 and Figure S5, Supporting Information).

Ex vivo biodistribution of [^{18}F]**ZCDD083** was initially studied in healthy female C57BL/6J mice (Table S2, Supporting Information). Measurement of radioactivity by γ-counter showed a high overall accumulation of [^{18}F]**ZCDD083** in tissues and organs within 2 h pi, as shown in Figure 2. More specifically, high blood radioactivity was observed (7.2 ± 2.2%ID/g at 15 min pi, 5.5 ± 1.6%ID/g at 1 h pi, and 2.1 ± 0.4%ID/g at 2 h pi), revealing a slow clearance of [^{18}F]**ZCDD083** from blood pool. Also, high pulmonary uptake was found (34.7 ± 6.0%ID/g at 15 min) with a slow washout from lungs (11.0 ± 1.5%ID/g at 2 h. On the contrary, at 6 h pi the radioactivity in lungs and blood was significantly lower (5.5 ± 3.9%ID/g and 1.5 ± 1.1%ID/g, respectively). Instead, at the late time point [^{18}F]**ZCDD083** had mostly accumulated in the excretory organs (i.e., 25.5 ± 3.8%ID/g in small intestine and 47.9 ± 6.4%ID/g in large intestine). Level of uptake in the liver and the intestines was significantly higher compared to the kidneys. Therefore, it can be concluded that [^{18}F]**ZCDD083** is predominantly cleared via the hepatobiliary system into the intestines and that the renal clearance is less significant.

Ex vivo biodistribution evaluation at 6 h pi was carried out also in atherosclerotic ApoE$^{-/-}$ mice (Table S3, Supporting Information). A similar [^{18}F]**ZCDD083** biodistribution profile was observed in atherosclerotic ApoE$^{-/-}$ and control C57BL/6J mice. Pharmacokinetic studies in ApoE$^{-/-}$ atherosclerotic mice confirmed the plasma half-life of [^{18}F]**ZCDD083** (1.4 ± 0.2%ID/g in blood). Residual high radioactivity accumulation was observed in lungs (8.6 ± 1.9%ID/g), whereas the maximal uptake was found in small and large intestine (40.6 ± 45.8% ID/g and 35.6 ± 2.3%ID/g, respectively).

[^{18}F]**ZCDD083** PET imaging scans were performed using two different disease models (ApoE$^{-/-}$, with moderate atherosclerosis, and ApoE$^{-/-}$Fbn1$^{C1039G+/-}$, with severe advanced atherosclerosis, both female) and aged-matched wild type C57BL/6J female mice as controls. Representative PET/CT scans of ApoE−/−Fbn1$^{C1039G+/-}$ mice are shown in Figure 3. Spherical ROIs were drawn manually over each aortic arch and ascending aorta using the axial view of CT images. The [^{18}F]**ZCDD083** signal was then quantified as SUV_{mean} (mean Standardized Uptake Values). Tracer uptake was different in ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ (SUV 0.78 ± 0.05),

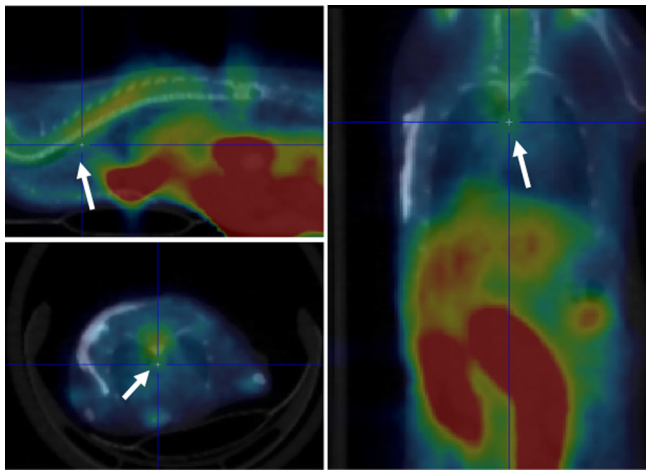

Figure 3. Representative axial, sagittal, and coronal views of PET/CT images of ApoE$^{-/-}$Fbn1C1039G$^{+/-}$ acquired at 6 h after injection of [^{18}F]**ZCDD083**. Radioactive signal in aorta (white arrows) was observed.

ApoE$^{-/-}$ (SUV 0.55 ± 0.06), and C57BL/6J mice (SUV 0.44 ± 0.09), with significant difference between first and latter series, as shown in Figure 4.

At the end of the PET imaging scans, three mice of C57BL/6J, ApoE$^{-/-}$, and ApoE$^{-/-}$Fbn1$^{C1039G±}$ were sacrificed and the

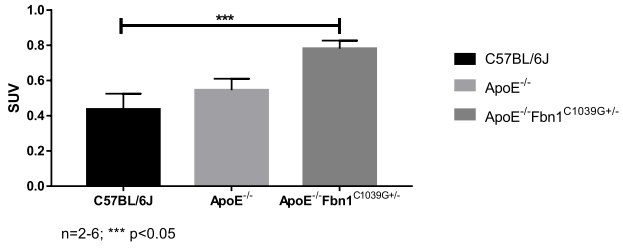

Figure 4. Comparison of SUV measurements in C57BL/6J (n = 6), ApoE−/− (n = 6), and ApoE$^{-/-}$Fbn1C1039G$^{+/-}$ mice (n = 2). All values are given as mean ± SD. One-way ANOVA was performed to test for difference between groups. One ApoE$^{-/-}$Fbn1C1039G$^{+/-}$ mouse was excluded from the analysis because of a PET image acquisition technicality. (***p = 0.0006, one-way ANOVA followed by Brown-Forsythe test).

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aorta was harvested for Red Oil O staining and autoradiography (ARG). The *ex vivo* distribution of atherosclerotic plaques within the aorta was assessed by Red Oil O staining, whereas the accumulation of [^{18}F]**ZCDD083** was assessed by autoradiography of the in vivo injected [^{18}F]**ZCDD083**. This aforementioned Red Oil O staining and *ex vivo* autoradiography were performed on the same aortic specimens in order to visually compare fat-stained areas and tracer distribution within the aorta (Figure 5).

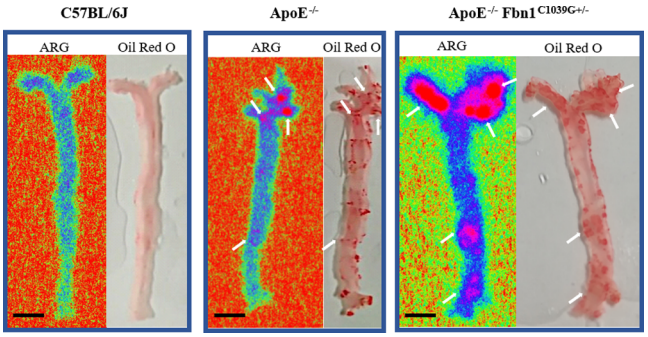

Figure 5. [^{18}F]**ZCDD083** aortic uptake vs plaque distribution. *Ex vivo* autoradiography (left part of the insets) and fat staining using Oil-red O (right part of the insets) of longitudinally opened aortas at 6 h post injection of [^{18}F]**ZCDD083** in C57BL/6J control mice (left) compared to atherosclerotic mice (ApoE$^{-/-}$ and ApoE$^{-/-}$Fbn1$^{C1039G+/-}$, center and right, respectively, as indicated by the white arrows. [^{18}F]**ZCDD083** uptake colocalizes with atherosclerotic plaques. Scale bar = 1 cm.

Aortas from C57BL/6J control mice did not show focal lipid stained areas and radioactivity signal. Conversely, atherosclerotic plaques were found in ApoE$^{-/-}$ mice, especially in the aortic arch, proximal aorta, and brachiocephalic aorta. The Oil Red O staining showed also a low plaque load in the thoracic descending aorta of the ApoE$^{-/-}$ strain. The ARG of the same specimen showed that the tracer accumulation within the aorta matched exactly with the distribution of atherosclerotic lesions. More specifically, the radioactivity was accumulated mostly in the aortic arch and in the branches. In these regions, [^{18}F]**ZCDD083** uptake was significantly higher in ApoE$^{-/-}$ (0.022 ± 0.004%ID/μL) than control mice (0.011 ± 0.003%ID/μL) (p = 0.0378, unpaired t test).

The correlation between plaques and tracer uptake was also consistent using ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ mice with higher plaque load than the ApoE$^{-/-}$ strain.[27] The comparison of corresponding *en face* lipid staining and ARG signals demonstrated a high correlation of fat-stained areas and radioactivity distribution. ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ mice showed more extended atherosclerotic lesions in the arch region, brachiocephalic artery, along with thoracic descending aorta. [^{18}F]**ZCDD083** was, indeed, detected in the same areas along the aorta.

Aortic specimens of C57BL/6J and ApoE$^{-/-}$ (n = 3/each group) were used for further histological analysis after PET imaging scans. Longitudinal sections of aortic arch and right common carotid artery as well as cross sections of brachiocephalic aorta and proximal aorta were stained with hematoxylin and eosin (H&E) to visualize atherosclerotic plaques and lesion morphology. Aortas of healthy mice did not show atherosclerosis, whereas ApoE$^{-/-}$ mice showed fibrous/atheromatous plaques and some small calcifications. The H&E staining confirmed atherosclerotic disease especially in brachiocephalic artery, proximal aorta, and aortic arch. The immunohistochemistry of ApoE$^{-/-}$ aortic arch sections revealed that the enzyme target PFKFB3 is overexpressed inside atherosclerotic plaques (see Figure S6, Supporting Information).

The comparison among brachiocephalic arteries of atherosclerotic and control mice showed that PFKFB3 was highly expressed within atherosclerotic plaques, whereas in normal vessels PFKFB3 is present just in a basal level along the arterial wall (Figure 6).

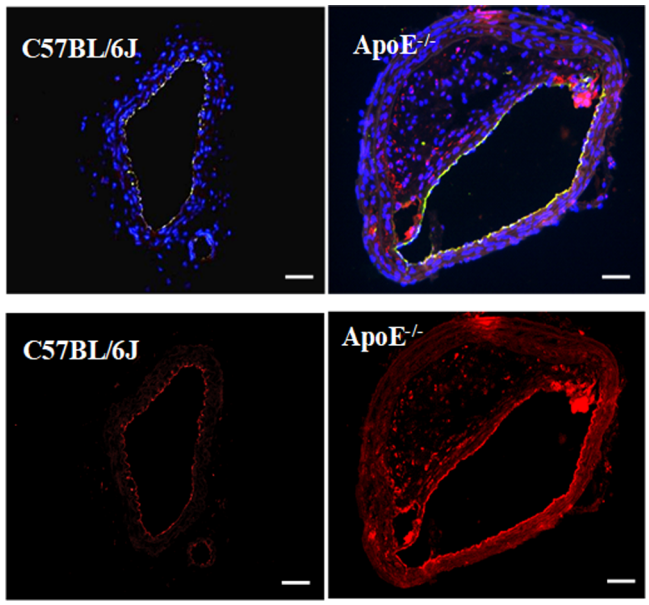

Figure 6. Immunohistochemistry of murine brachiocephalic arteries. Upper panels = immunofluorescent staining for von Willebrand factor to detect endothelial cells (green) and PFKFB3 (red). Counterstaining with DAPI to detect nuclei (blue). Lower panels = PFKFB3 staining (red). ApoE$^{-/-}$ mice exhibit high expression level of PFKFB3 enzyme in contrast to C57BL/6J controls. Scale bar = 50 μm.

DISCUSSION

Atherosclerosis is responsible for the majority of acute cardiovascular events. Specifically, rupture of atherosclerotic plaques and consequent thrombosis remains the largest underlying cause of cardio- and cerebrovascular death. Despite extraordinary advances in the understanding of the pathophysiology of atherosclerosis, both the diagnosis and treatment of the disease still present limitations. Currently, the main challenge in cardiovascular medicine is to identify patients who are at risk of coronary plaque rupture and subsequent heart attack or stroke originating from carotid plaque depositions.[15] Among the cardiovascular imaging modalities used, coronary angiography has a wide clinical application but provides information only on vessel stenosis. Other imaging techniques, such as intravascular ultrasound (IVUS), optical coherence tomography (OCT), and near-infrared spectroscopy (NIRS), can provide only a limited plaque characterization, but unfortunately, they are invasive and thus not useful for patient diagnosis and follow up.[16−18] Therefore, new noninvasive approaches to detect potentially unstable plaque are urgently needed.

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In this context, PET imaging has great potential, since—compared to other molecular imaging modalities—it shows higher sensitivity allowing better visualization of biological and biochemical processes involved in the development of atherosclerotic plaques.[19] [^{18}F]FDG (inflammation, approved for clinical use) and [^{18}F]NaF (microcalcification) have been investigated in a clinical setting for detection and characterization of atherosclerotic plaques in the major coronary arteries.[19,20] However, new targets and radiotracers are currently being investigated preclinically for imaging atherosclerotic plaque.[21] Clinical studies showed that [^{18}F]-FDG is useful to assess carotid artery stenosis in asymptomatic patients.[22,23] However, carotid artery imaging using [^{18}F]-FDG PET is challenging due to (1) the low spatial resolution of PET (≈3 mm in human PET and 1.2 mm in rodent PET, using our setting), (2) cardiac motion, and (3) myocardial spill over.[24] To address the latter limitation, new imaging targets and radiotracers having lower unspecific myocardial uptake are currently under investigation.[25]

The results above validate the PFKFB3 enzyme as an imaging target of atherosclerosis in two mouse models.[26,27] First, we observed—via PET/ARG—an increased target engagement in cross sections of diseased aortas of atherosclerotic mice compared to those of healthy mice. Second, longitudinal sections of aortic arch specimens of ApoE$^{-/-}$ mice showed higher expression level of PFKFB3 enzyme within atherosclerotic plaques compared to normal vessel wall. Hence, all these results demonstrated the appropriateness and the specificity of the PFKFB3 target for the detection of atherosclerotic plaques.

The new PFKFB3-targeted tracer, [^{18}F]**ZCDD083** could be obtained in high radiochemical yields, activity concentrations, and quality parameters. [^{18}F]**ZCDD083** demonstrated high *in vivo* metabolic stability and long circulation time in the blood. The slow clearance from the blood may be explained by the high hydrophobicity of [^{18}F]**ZCDD083**. Indeed, a $LogD_{7.4}$ of 3.6 was reported for the parent compound **AZ68**.[14] The correlation of high hydrophobicity with high binding to plasma proteins and prolonged circulation time in the blood is well-known.[28] High binding to plasma proteins is documented for the compound **AZ26**[14] (chemically similar to **AZ68**) and might be valid also for our tracer [^{18}F]**ZCDD083**. This may likely explain the slow tracer clearance. Also, the excretion route is usually related to lipophilicity, as lipophilic compounds are generally cleared via the hepatobiliary system. This is in accordance with our *ex vivo* biodistribution results which showed a predominant excretion from the liver to the intestines. We also noticed a high uptake in the lung. However, it is not clear whether this high uptake in the lung is due to nonspecific binding (due to the high [^{18}F]**ZCDD083** lipophilicity) or somehow correlated with PFKFB3 tissue distribution. In 2003, Minchenko et al. studied the *in vivo* expression of the PFKFB enzyme family and its response to hypoxia, disclosing that lungs exhibit high basal level of PFKFB3 mRNA.[29] Furthermore, it was recently shown that lung endothelial cells express high levels of glucose metabolic enzymes, such as PFKFB3.[30] Finally, the proteome analysis reported in the Human Protein Atlas shows that lung, stomach, and placenta have the highest PFKFB3 expression among all tissues considered.[31]

Our PET imaging studies showed significantly increased signals in the aorta of ApoE$^{-/-}$ (+25%) and ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ (+79%) compared to C57BL/6J mice. This is in accordance with the higher plaque burden in ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ mice compared to ApoE$^{-/-}$ mice.[27] Moreover, these results were supported by aortic autoradiography which showed a 2-fold increased uptake in the aortic arch of ApoE$^{-/-}$ compared to WT mice. The autoradiographic signal in ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ was considerably higher too. The increment in uptake is clearly correlated with the increment in plaque load, as confirmed by histological evaluation. Indeed, the highest uptake was found in ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ at an advanced stage of the disease and high level of plaques in the aortic arch along with the thoracic aorta.

Unfortunately, despite the higher uptake, the [^{18}F]**ZCDD083** signal in these small sized atherosclerotic plaques was affected by partial volume effect and, due to the limited spatial resolution of PET,[32] no "hotspots" could be detected in the *in vivo* imaging studies. Indeed, the vessel wall in mouse aorta is usually 30−80 μm, whereas the resolution in rodent PET imaging is ∼1,2 mm.

The specificity of the tracer accumulation at the target structure (i.e., atherosclerotic plaque) was demonstrated by the combination of *ex vivo* autoradiography with *en face* Oil Red O staining of the same aortic specimens. Indeed, we observed colocalization of [^{18}F]**ZCDD083** signal with plaque distribution along the aorta. These cross studies, involving C57BL/6J, ApoE$^{-/-}$ and ApoE$^{-/-}$Fbn1$^{C1039G+/-}$ demonstrated high sensitivity of [^{18}F]**ZCDD083** to detect atherosclerotic plaques, whereas little signal was detected in normal vessel or outside atherosclerotic lesions. These stained areas exhibited a higher tracer accumulation. Hence, the [^{18}F]**ZCDD083** uptake was clearly correlated with plaque distribution as well as with the progression of the disease.

CONCLUSION

In summary, we efficiently radio-synthesized the novel PET tracer [^{18}F]**ZCDD083** which targets the PFKFB3 enzyme. Using *in vivo* and *ex vivo* studies, we characterized and validated [^{18}F]**ZCDD083**, demonstrating its ability to detect atherosclerotic plaques. This tracer may represent a promising tool for the noninvasive diagnosis and follow-up of atherosclerotic plaques prone to rupture, which in turn could help improve risk stratification and evaluation of the efficacy of antiatherosclerotic therapies.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsmedchemlett.9b00677.

Experimental procedures for the synthesis of all the compounds described in this paper, radiochemistry procedures for [^{18}F]**ZCDD083**, animal models, *in vivo* metabolite analysis, *ex vivo* biodistribution, PET/CT imaging, autoradiography, and histology. Copies of the ^{1}H, ^{19}F, and ^{13}C NMR spectra of all the new compounds. (PDF)

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Author Contributions

CDD performed and codesigned all the experiments and contributed to writing the manuscript. SDA designed and performed radiochemistry experiments and contributed to writing the manuscript. LW designed and performed radiochemistry experiments and reviewed the manuscript. SS designed *in vivo* experiments and reviewed the manuscript. GDM designed biology experiments and reviewed the manuscript. MZ designed the experiments and wrote the manuscript.

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

CCR2, CC chemokine receptor 2; CCL2, CC chemokine ligand 2; CCR5, CC chemokine receptor 5; TLC, thin layer chromatography.

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