Improving metabolic stability of fluorine-18 labeled verapamil analogs

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Introduction: Fluorine-18 labeled positron emission tomography (PET) tracers were developed to obtain more insight into the function of P-glycoprotein (P-gp) in relation to various conditions. They allow research in facilities without a cyclotron as they can be transported with a half-life of 110 min. As the metabolic stability of previously reported tracers [18F]1 and [18F]2 was poor, the purpose of this study was to improve this stability using deuterium substitution, creating verapamil analogs [18F]1-d4, [18F]2-d4, [18F]3-d7, and [18F]3-d7.

Methods: The following deuterium containing tracers were synthesized and evaluated in mice and rats: [18F]1-d4, [18F]2-d4, [18F]3-d7, and [18F]3-d7.

Results: The deuterated analogs [18F]2-d4, [18F]3-d7, and [18F]3-d7 showed increased metabolic stability compared with their non-deuterated counterparts. The increased metabolic stability of the methyl containing analogs [18F]3-d7 might be caused by steric hindrance for enzymes.

Conclusion: The striking similar in vivo behavior of [18F]3-d7 to that of (R)-[11C]verapamil, and its improved metabolic stability compared with the other fluorine-18 labeled tracers synthesized, supports the potential clinical translation of [18F]3-d7 as a PET radiopharmaceutical for P-gp evaluation.

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1. Introduction

P-glycoprotein (P-gp) is an ATP dependent efflux transporter, which is i.a. located on the luminal side of the blood-brain barrier [1]. As such, it mediates the transport of structurally diverse compounds from brain to blood, thereby protecting the brain from xenobiotics. P-gp is the most studied ATP-binding cassette (ABC) transporter and it is linked to various neurodegenerative diseases. It has been shown that P-gp function is diminished in Alzheimer’s disease, which may accelerate the disease process, as it is associated with decreased clearance of β-amyloid from the brain [2]. On the other hand, several studies have shown increased P-gp function in epilepsy patients, associated with resistance to anti-epileptic drugs [3]. To obtain more insight into the function of P-gp in relation to these and other conditions, positron emission tomography (PET) can be used to investigate the function of P-gp in vivo using substrates labeled with positron emitters [4]. (R)-[11C]Verapamil is a commonly used PET agent for P-gp research, although limited by its relatively short half-life of 20 min. Originally, verapamil was developed and used as a calcium channel blocker [5], but it is also a substrate of P-gp.

Recently, two fluorine-18 labeled positron emission tomography (PET) tracers were developed [6] ([18F]1 and [18F]2, Fig. 1) to image the function of P-gp in the brain, based on the chemical structure of verapamil. Clearly, these tracers could be useful in clinical studies of Alzheimer’s disease or epilepsy, where alterations in P-gp function could be detected in a PET scan by increased or decreased brain uptake. Despite their high specificity for P-gp, a disadvantage of these tracers was their poor metabolic stability, as this may compromise quantification, decrease the signal-to-noise ratio and complicate interpretation.

The metabolic pathway of verapamil has been studied in detail [7,8]. Different metabolites were identified and the most important initial metabolites were D-617, norverapamil and D-703. The metabolites and corresponding enzymes are depicted in Fig. 2 [9, 10]. Previous PET studies have shown the formation of corresponding radiolabeled metabolites of (R)-[11C]verapamil in vivo [11]. It is known that N-demethylation of verapamil by cytochrome P450 enzyme, yielding the metabolite norverapamil occurs via the hydrogen atom transfer (HAT) mechanism [12]. Within this reaction, first a hydrogen atom (H) is abstracted creating a radical carbon atom. Next, an alcohol is formed which is cleaved of to form formaldehyde and a secondary amine. Deuterium substitution of the methyl group could be used to slow down this reaction. Cleavage of the covalent bond of carbon (C) with deuterium (D) requires greater energy than cleavage of the bond with hydrogen, due to the higher mass of deuterium.
compared with hydrogen. C–D bonds have a lower vibrational frequency and, thus, lower zero-point energy than an analogous C–H bond. This results in higher activation energy and slower rate for C–D bond cleavage. This rate effect is referred to as the primary deuterium isotope effect [13–15].

The deuterium substitution approach has been used on a number of occasions to fine-tune properties of new pharmaceuticals, primarily related to metabolic stability. The first approval of a deuterium containing drug was provided by the FDA for deutetrabenazine, issued 3rd of April 2017 [16,17]. In addition, in developing new PET tracers, deuterium has occasionally been used to alter properties. The first and most well-known deuterated PET tracer is [11C]-depropyl-D3, which showed slower binding to its target MAO B than the original hydrogen compound resulting in a reduced rate of trapping in (brain) tissue and to improve sensitivity [18]. Multiple deuterated analogs of [1H]- and [13C]-choline showed improved protection against choline oxidation [19,20]. Another example is [18F]deuteroaltanserin, which showed 29% higher ratios of parent tracer to radiometabolites in plasma, compared with [18F]altanserin [21].

In this study, four deuterium substituted analogs were synthesized and evaluated for metabolic stability and in vivo behavior. The purpose of this work is to develop a stable fluorine-18 PET tracer for P-gp evaluation, to gain more insight in the metabolic pathways and to investigate which groups are more prone to metabolism.

2. Materials & methods

2.1. General

Chemicals and solvents were purchased from commercial sources Sigma-Aldrich (Zwijndrecht, the Netherlands), Fluorochem (Hadfield Derbyshire, UK), ABCr GmbH (Karlsruhe, Germany) and Biosolve (Valkenswaard, the Netherlands) without further purification unless stated otherwise. Deuterated starting materials ethylene-d4 glycol, 2-bromoethanol-1,1,2,2-d4 and iodomethane-d3 had an isotopic purity of 98, 98 and ≥99.5 atom % D, respectively. (R)-desmethyl-verapamil was kindly donated by Abbott Laboratories (Lake Bluff, IL, USA). Dichloromethane (DCM), 1,2-dichloroethane (DCE), methanol (MeOH) and dimethylformamide (DMF) were dried over 3 Å molecular sieves, for at least 24 h prior to use. Tetrahydrofuran (THF) was first distilled from LiAlH4 and then dried over 3 Å molecular sieves. Thin layer chromatography (TLC) was performed on Merck (Darmstadt, Germany) precoated silica gel 60 F254 plates. Spots were visualized by UV quenching or ninhydrin. Column chromatography was carried out either manually by using silica gel 60 Å (Sigma-Aldrich) or on a Buchi (Flawil, Switzerland) sepacore system (comprising of a C-620 control unit, a C-660 fraction collector, 2 C-601 gradient pumps and a C-640 UV detector) equipped with Buchi sepacore prepacked flash columns. 1H and 13C nuclear magnetic resonance (NMR) spectra were recorded.

Fig. 1. Chemical structures of deuterated (nor-)verapamil analogs, with measured Log D values.

Fig. 2. Metabolic pathway of (R) [13C]verapamil as adapted from Luurtsema et al. [11].
on a Bruker (Billerica, USA) Avance 500 (500.23 MHz and 125.78 MHz, respectively) with chemical shifts (δ) reported in ppm relative to the solvent. Electrospray ionization mass spectrometry (ESI-MS) was carried out using a Bruker microTOF-Q instrument in positive ion mode (capillary potential of 4500 V). Solid-phase extraction cartridges (tC18 plus and Alumina N) were purchased from Waters Corp. (Milford, MA, USA).

Semi-preparative HPLC was performed on a Jasco PU-2089 pump station (Easton, MD, USA) equipped with either a Luna C18(2) column (10 μm, 250 mm × 10 mm, Phenomenex, California, USA) using H2O/MeCN/TFA (60:40:0.2, v/v/v) method: A) or 5 mM K2PO4/MeCN (28:72, %v/v, pH = 10.0, method: B) as eluent, or a Grace Altima column (10 μm, 250 mm × 22 mm; Hichrom, Theale, Berkshire, UK) using H2O/MeCN/TFA (50:50:0.1, %v/v/v, method: C) as eluent at a flow rate of 4 mL·min⁻¹, a Jasco UV-2075 Plus UV detector (λ = 254 nm), a custom made radioactivity detector and Jasco ChromNAV CFR software (version 1.14.01) for data acquisition. Quantitative analysis was performed using an HPLC system of Jasco containing a PU-2089 pump station equipped with a Grace Altima C18 column (5 μm, 250 mm × 4.6 mm) using H2O/MeCN/DIPA (40:60:0.1, %v/v/v, method: D); H2O/MeCN/TFA (50:50:0.1, %v/v/v, method: E) or H2O/MeCN/TFA (40:60:0.1, % v/v/v, method: F) as eluent at a flow rate of 1 mL·min⁻¹, with a Jasco UV-2075 UV detector (λ = 222 nm) and a Sodium Iodide (NaI) radioactivity detector (Raytest, Straubenhardt, Germany). Chromatograms were acquired using Raytest GINA Star software (version 5.01).

Metabolite analysis was performed on Dionex (Sunnyvale, CA, USA) UltiMate 3000 HPLC equipment with Chromeleon software (version 6.8). A ALUNA C8 (5 μm, 250 mm × 10 mm, Phenomenex (Torrance, CA, USA)) column was used. Quantitation was performed using an HPLC system of Jasco containing a PU-2089 pump station equipped with a Grace Altima C18 column (10 μm, 250 mm × 10 mm, Phenomenex, California, USA) using H2O/MeCN/TFA (60:40:0.2, v/v/v) method: A) or 5 mM K2PO4/MeCN (28:72, %v/v, pH = 10.0, method: B) as eluent, or a Grace Altima column (10 μm, 250 mm × 22 mm; Hichrom, Theale, Berkshire, UK) using H2O/MeCN/TFA (50:50:0.1, %v/v/v, method: C) as eluent at a flow rate of 4 mL·min⁻¹, a Jasco UV-2075 Plus UV detector (λ = 254 nm), a custom made radioactivity detector and Jasco ChromNAV CFR software (version 1.14.01) for data acquisition. Quantitative analysis was performed using an HPLC system of Jasco containing a PU-2089 pump station equipped with a Grace Altima C18 column (5 μm, 250 mm × 4.6 mm) using H2O/MeCN/DIPA (40:60:0.1, %v/v/v, method: D); H2O/MeCN/TFA (50:50:0.1, %v/v/v, method: E) or H2O/MeCN/TFA (40:60:0.1, % v/v/v, method: F) as eluent at a flow rate of 1 mL·min⁻¹, with a Jasco UV-2075 UV detector (λ = 222 nm) and a Sodium Iodide (NaI) radioactivity detector (Raytest, Straubenhardt, Germany). Chromatograms were acquired using Raytest GINA Star software (version 5.01).

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2.1.6. tert-Butyl (4-(2-fluoroethoxy-1,1,2,2-d₄)-3-methoxyphenethyl) carbamate (11)

2-(4-((tert-Butyloxy carbonyl) amino)ethyl)-2-methoxyphenoxy)ethyl-d₄ 4-methylbenzenesulfonate (471 mg, 1.00 mmol) and TBAF (446 mg, 1.71 mmol) were co-evaporated three times with dry acetonitrile to remove any water. Compounds were dissolved in acetonitrile in hexane to obtain the desired clear solution (254 mg, 0.800 mmol, 80%). ¹H NMR (CDCl₃) δ 6.88–6.71 [3H, m, CH₃], 4.55 [1H, br, s, NH], 3.87 [3H, s, OCH₃], 3.36 [3H, q, J = 6.6 Hz, NCH₂CH₃], 2.75 [2H, t, J = 7.0, NHCH₂CH₃], 1.44 [9H, s, Boc]. ¹³C NMR (CDCl₃) δ 155.71, 149.52, 146.15, 132.00, 120.51, 114.34, 112.44, 78.85, 55.61, 41.65, 35.54, 28.17. ESI-HRMS: calculated for C₁₅H₂₃d₄FNO₄: 317.1940, 340.1856 [M + Na]⁺ found.

2.1.7. 2-(4-(Fluoroethoxy)-1,1,2,2-d₄)-3-methoxyphenoxy)ethan-1-amine (12)

tert-Butyl (4-(2-fluoroethoxy)-3-methoxyphenethyl-d₄)carbamate (253 mg, 0.797 mmol) was dissolved in DCM (12 mL). TFA (12 mL) was added and the mixture was stirred at room temperature for 1 h. Reaction mixture was diluted with DCM and solvent was evaporated under vacuo. Crude mixture was purified by flash column chromatography (3–5% MeOH in DCM) to obtain the desired product as a white solid (174 mg, 0.800 mmol, quantitative yield). ¹H NMR (MeOD) δ 6.95–6.78 [3H, m, CH₃], 3.85 [3H, s, OCH₃], 3.16 [2H, t, J = 7.6 Hz, NHCH₂CH₃], 2.50 [2H, t, J = 8.0 Hz, NCH₂CH₃]. ¹³C NMR (CDCl₃) δ (ppm) 151.57, 148.78, 131.72, 122.32, 116.09, 114.20, 56.61, 42.15, 34.30. ESI-HRMS: calculated for C₁₅H₂₀d₄FNO₂: 217.1416, 218.1559 [M + H]⁺ found.

2.1.8. (R)-(2-(4-(Fluoroethoxy)-1,1,2,2-d₄)-3-methoxyphenoxy)ethyl-3-iso-propylpentanenitrile (18)

2-(4-(2-Fluoroethoxy)-3-methoxyphenethyl-d₄)amine (174 mg, 0.800 mmol) was dissolved in dry MeOH (3 mL) and Na₂SO₄ (600 mg, 4.2 mmol) was added. (R)-2-(3,4-dimethoxyphenyl)-2-isopropyl-5-oxopentanenitrile (147 mg, 0.534 mmol) was dissolved in dry MeOH (1.4 mL). After the reaction mixture was stirred at room temperature overnight under nitrogen. Sodium triacetoxycarbonyl (170 mg, 0.800 mmol) was added and stirred at room temperature for 2 h. The reaction was quenched with 1 M NaHCO₃ and extracted with EtOAc, washed with water and brine, dried over Na₂SO₄ and the solvent was evaporated in vacuo. The crude oil was purified by column chromatography (3–7% MeOH in DCM) to obtain the desired product as a white solid (124 mg, 0.201 mmol, 37% yield). ¹H NMR (CDCl₃) δ 6.84–6.71 [3H, m, CH₃], 4.15 [2H, t, J = 4.4 Hz, CH₂CH₂OTs], 4.15 [2H, t, J = 4.4 Hz, CH₂CH₂OTs], 3.84 [3H, s, OCH₃], 3.80 [3H, s, OCH₃], 3.78–3.69 [3H, m, CH₃]. ¹³C NMR (CDCl₃) δ 151.76, 151.14, 150.49, 148.46, 146.66, 134.45, 131.45, 131.32, 131.20, 129.21, 122.20, 121.16, 120.56, 116.67, 114.27, 112.98, 110.94, 65.79, 57.60, 56.58, 56.51, 38.88, 35.48, 32.34, 30.88, 23.91, 22.34, 21.76, 19.50, 19.03. ESI-HRMS: calculated for C₁₅H₂₀d₄FNO₂S: 645.3465, 646.3498 [M + H]⁺ found.

2.1.10. (R)-2-(4-((4-cyano-4-(3,4-dimethoxyphenyl)-5-methylhexyl)amino)ethyl)-2-methoxyphenoxy)ethyl-4-methylbenzenesulfonate (19)

2-(4-(3-Aminoethyl)-2-methoxyphenoxy)ethyl 4-methylbenzenesulfonate (341 mg, 0.935 mmol) and (R)-2-(3,4-dimethoxyphenyl)-2-isopropyl-5-oxopentanenitrile (177 mg, 0.644 mmol) were stirred together with iodomethane (174 mg, 0.801 mmol) and Na₂SO₄ (613 mg) in 3 mL dry MeOH. The reaction mixture was stirred overnight at room temperature. The reaction mixture was purified by flash column chromatography (2% MeOH in DCM) and HPLC (method C) to obtain the product as a white solid (5 mg, 0.007 mmol, 2% yield). ¹H NMR (MeOD) δ 7.81 [2H, d, J = 8.2 Hz, SO₂-CH₂Ar], 7.42 [2H, d, J = 8.2 Hz, CH₂-CH₂Ar], 7.04–6.67 [6H, m, CH₃], 3.84 [3H, s, OCH₃], 3.82 [3H, s, OCH₃], 3.80 [3H, s, OCH₃], 3.15–2.88 [4H, m, CH₂CH₂Ar], 2.22–2.03 [3H, m, CH(CH₃)₂] and COCH₃, 1.75 and 1.38 [1H each, br, s, CH₃CH₂CH₂Ar], 1.31 [2H, br, s, NCH₂CH₂Ar], 1.22 and 0.79 [3H each, d, J = 6.6 Hz, CH(₃)CH₂]. ¹³C NMR (CDCl₃) δ 151.78, 151.16, 150.51, 148.49, 146.65, 134.48, 131.46, 131.26, 131.20, 129.21, 122.21, 122.16, 120.56, 116.64, 114.27, 112.98, 110.94, 56.79, 57.60, 56.58, 56.51, 38.88, 35.48, 32.34, 30.88, 23.91, 22.34, 21.76, 19.50, 19.03. ESI-HRMS: calculated for C₁₆H₂₂d₄FNO₃S: 654.3465, 646.3498 [M + H]⁺ found.

2.1.11. (R)-2-(3,4-dimethoxyphenyl)-5-((4-(2-fluoroethoxy)-3-methoxyphenethyl)(methyl-d₄)amine)ethyl-2-methoxyphenoxy)ethyl-4-methylbenzenesulfonate (20)

(R)-2-(3,4-dimethoxyphenyl)-2-isopropyl-5-oxopentanenitrile (174 mg, 0.534 mmol) was dissolved in 1.4 mL MeOH and added to a suspension of 2-(4-(2-fluoroethoxy)-3-methoxyphenethyl)(ethane-d₄)amine (174 mg, 0.801 mmol) and Na₂SO₄ (613 mg) in 3 mL dry MeOH. The reaction mixture was stirred overnight at room temperature under nitrogen. Sodium triacetoxycarbonyl (170 mg, 0.801 mmol) was added and the mixture was stirred again at room temperature for 2 h. The reaction was quenched with 1 M NaHCO₃ and extracted with EtOAc, washed with water and brine, dried over Na₂SO₄ and solvent was removed in vacuo. The crude mixture was purified by flash column chromatography (2–7% MeOH in DCM) to obtain the desired product as a white solid (50 mg, 0.019 mmol, 3% yield). ¹H NMR (MeOD) δ 6.71 [3H, m, CHAR], 4.77 [2H, dt, J = 47.4 and 4.2 Hz, CH₃CH₂F], 4.25 [2H, dt, J = 27.8 and 4.3 Hz, CH₃CH₂F], 3.89.
Scheme 1. Reagents and conditions: TsCl, Et3N, DCM, 0 °C, 1 h (4 to 6) or 16 h (5 to 7).

Scheme 2. Reagents and conditions: i) 7, Cs2CO3, DMF, r.t., 4 h; ii) TBAF, MeCN, 85 °C, 4 h; iii) TFA, DCM, r.t., 1 h.
2.3. General procedure for log \( D_{7.4} \) measurements

The distribution of the tracers between equal volumes of 0.2 M phosphate buffer (pH = 7.4) and 1-octanol was measured in triplicate at room temperature. 1 mL of a 1–5 MBq·mL\(^{-1}\) solution of the fluorine-18 labeled tracers in 0.2 M phosphate buffer (pH = 7.4) was vigorously mixed with 1 mL of 1-octanol for 1 min at room temperature using a vortex. After 30 min, five samples of 100 \( \mu \)L were taken from both layers, avoiding cross-contamination. To determine recovery, 5 samples of 100 mL were taken from the 1–5 MBq·mL\(^{-1}\) solution. All samples were counted for radioactivity. The Log \( D_{7.4} \) value was calculated according to \( \log D_{7.4} = 10 \log (A_{\text{oct}}/A_{\text{buffer}}) \), where \( A_{\text{oct}} \) and \( A_{\text{buffer}} \) represent average radioactivity of 5 1-octanol and 5 buffer samples, respectively [23].

2.4. Animals

Healthy male Wistar rats were obtained from Harlan Netherlands B.V. (Horst, the Netherlands) and male FVB wild-type mice and \( \text{Mdr1a/b}^{\text{−/−}} \) mice developed from the FVB line were purchased from Taconic (Hudson, USA). All animals were housed in groups of four to six per cage under standard conditions (24 °C, 60% relative humidity, 12-h light/dark cycles) and provided with water and food (Teklad Global 16% ProteinRodent Diet, Harlan, Madison, WI, USA) ad libitum. All animal experiments were performed in compliance with Dutch laws on animal experimentation (‘Wet op de proefdieren’, Stb 1985, 336) and after approval by the local animal ethics committee.

2.5. Metabolite analysis

Under isoflurane anesthesia, healthy Wistar rats (198–286 g) received tail vein injection of 36.8 ± 5.7, 30.2 ± 5.0, 24.4 ± 5.2 or 38.6 ± 6.1 MBq of \([^{18}\text{F}][1\text-d_4], [^{18}\text{F}][2\text-d_4], [^{18}\text{F}][3\text-d_3], [^{18}\text{F}][3\text-d_7] \) respectively, in 0.2–0.4 mL. After injection, rats were conscious for the allowed time (except for the animals of the 5 min time point, which were left unconscious for the whole time) and sacrificed under isoflurane anesthesia at 5, 15 or 60 min (\( n = 3 \) for each time point). Blood samples were collected via a heart puncture, and the brain was removed from the skull and cut in half. Blood was collected in a heparin tube and centrifuged for 5 min at 4000 rpm (Hettich universal 16, Depex B.V., the Netherlands). Plasma was separated from blood cells, 1 mL plasma was loaded onto a Sep-Pak tC18 cartridge (Waters, Etten-Leur, the Netherlands), and the cartridge was washed with 20 mL of water. This eluate was defined as the polar radiolabeled metabolite fraction. Next, the Sep-Pak cartridge was eluted with 1.5 mL of methanol. This eluate was defined as the non-polar fraction, and also contains the parent tracer. It was analyzed using HPLC (method G). The recovery from the Sep-pak procedure was \( \sim 85\% \) and rest activity was not taken into account. One half of the brain was counted for activity and the other half was homogenized with an ultrasonic homogenizer (Braunsonic 1510, ...
Table 1
Parent tracer and radiolabeled metabolite fractions in plasma (% of total radioactivity, mean ± SD; after intravenous injection of tracers under isoflurane anesthesia); for chemical structures, see Fig. 1.

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2.6. PET imaging and data analysis

Mice (25–32 g; Mdr1a/b–/−; mice: n = 3; WT mice: n = 4) were anesthetized via a nose mask using 2% isoflurane in oxygen at a rate of 1 L min⁻¹. One hour prior to each study, a jugular vein was cannulated for administration of the tracer. Animals were scanned on small animal NanoPET/CT or NanoPET/MR scanners (Mediso Ltd., Budapest, Hungary) [24] with identical PET components. The CT was used for at-

dult administration of the tracer. The deprotected amine bound methyl group of verapamil, two other analogs of [18F]2 were synthesized, [18F]3-d4 and [18F]3-d4, both with a deuterated methyl group. The difference between these two analogs was the (non-)deuterated fluoroethyl group.

3.1. Chemistry

The syntheses of the precursors and reference compounds were almost identical to those of the non-deuterated compounds, which have been de-
This resulted in enough product to perform animal experiments.

For the reference compound of $[^{18}F]2$, the reference compound of $[^{18}F]2$ was used [6] and methylated with lodomethane-$d_3$.

Since the reference compound was used to identify the tracers by co-elution on analytical HPLC, the effect of deuterium substitution on elution time was tested. No difference in elution time between $[^{18}F]2$ and $[^{18}F]2-d_4$ was observed for different HPLC systems and therefore the reference compound of $[^{18}F]1$ could be used for $[^{18}F]1-d_4$ and the reference compound of $[^{18}F]3-d_3$ for $[^{18}F]3-d_7$.

3.2. Radiochemistry

2-Bromoethanol-$d_4$ was tosylated (Scheme 1) and the purified oil was used as such to synthesize $[^{18}F]1-d_4$ (Scheme 4). For $[^{18}F]1-d_4$, the same method was used as described before [6], where 2-bromoethyltosylate-$d_4$ was fluorinated and distilled to a second vial. On average 25% of $[^{18}F]21$ was distilled to the second vial. The conversion of the second step to $[^{18}F]2-d_4$, varied from 5% to 27% and stirring was necessary to obtain product with a total yield of 2.64 ± 2.26% DC ($n = 7$). This resulted in enough product to perform animal experiments.

$[^{18}F]2-d_4$ was radiolabeled as previously described [6], with direct fluorination and deprotection of the Boc group to result in a total yield of 6.10 ± 2.62% DC ($n = 3$) (Scheme 5).

$[^{18}F]3-d_3$ and $[^{18}F]3-d_7$ were radiolabeled in exactly the same manner, i.e. by direct fluorination on the tosyl group. Purification was challenging since traces of unlabeled fluoride were found in the product. To circumvent this, a purification step with an Alumina Sep-Pak was introduced to trap free and unreacted $[^{18}F]$fluorine on the Sep-Pak, before HPLC purification. This resulted in collected product with a radiochemical purity >99.5% and a total yield of 2.74 ± 0.71% DC ($n = 3$) and 4.90 ± 3.86% DC ($n = 5$) for $[^{18}F]3-d_3$ for $[^{18}F]3-d_7$, respectively. As the precursors were not 99.9% pure, an additional radiochemical purity check was included using an HPLC system with a different column and eluent.

3.3. Metabolite study

Metabolite analyses of four novel tracers were performed in healthy Wistar rats, 5, 15 and 60 min after tracer injection. As the focus of the present study was on the comparison of stabilities of analog compounds, only male animals were used in order to avoid possible variation due to gender differences. In order to exclude possible differences in vivo behavior of the tracers due to gender differences, a follow-up study should be performed for the most promising analog. This is beyond the scope of the present study. Statistical analysis of the metabolite data was performed using two-tailed unpaired $t$-tests. For plasma (Table 1), no improvement in metabolic stability was observed when moving from the hydrogenated to the deuterated $[^{18}F]1$ tracer. On the other hand, for the $[^{18}F]2[d-d_4]$ analogs, an significant improvement in stability due to the deuterated fluoroethyl group was observed ($p < 0.05$, for 5 and 15 min). This could indicate that a different metabolic pathway for $N$-defluoroethylation takes place, where the C—D bond is not included in the rate limiting step. Nonetheless, $[^{18}F]2-d_4$ was less stable in plasma than non-deuterated $[^{18}F]1$. It seems that the tertiary amine slows down the metabolic rate, possibly by steric hindrance. To test this hypothesis, a deuterated methyl group on the amine was added in additional analogs, i.e. $[^{18}F]3-d_4$ and $[^{18}F]3-d_7$, without and with the deuterated fluoroethyl group on the phenolic side.

The addition of a deuterated methyl group on the amine showed even higher in vivo stability. This actually contradicts the first assumption in the design of $[^{18}F]2$ [6], which was based on the postulation that removal of the methyl group would circumvent the first metabolic step (demethylation). Nevertheless, adding a deuterated methyl group

**Fig. 3.** Whole brain time-activity curves of a) $[^{18}F]3-d_7$, b) (R) $[^{11}C]$verapamil and c) $[^{18}F]2$ in i) wild-type (WT) mice and ii) Mdr1a/b$^{-/-}$ mice [6]. d) Ratio of Mdr1a/b$^{-/-}$ SUV over WT SUV with $[^{18}F]3-d_7$, $[^{18}F]2$ and (R) $[^{11}C]$verapamil. Mice were injected with 3–4 MBq of $[^{18}F]3$ under isoflurane anesthesia for 60 min.
on the amine still served the purpose of avoiding fluorine-18 labeled metabolites, which may also act as substrates of P-gp. For almost all tracers, primarily polar metabolites were formed, which are not expected to penetrate the BBB and therefore will not interfere with the PET signal. Interestingly, [18F]3d7 showed a different pattern with more labeled non-polar metabolites in plasma. This might reflect a metabolite that is formed after metabolic cleavage of the C–N bond on the stereoselective side of the molecule, with the deuterated methyl group still attached.

Brain tissue showed a different distribution between parent tracer and metabolites because some metabolites do not cross the blood-brain barrier. In the brain (Table 2), significantly more parent [18F]1-d4 is present compared with [18F]1 (p < 0.0005 at 15 min). For [18F]2, an increased parent fraction for the deuterated analog is even more prevalent (p = 0.05 at 5 and 15 min). Similar to the pattern in plasma, the combination of deuterated methyl and fluorophenyl groups ([18F]3-d7) results in the highest fraction of parent tracer, until the 60 min time point, when [18F]2-d4 showed the highest parent fraction in the brain.

3.4. PET study

To assess in vivo behavior, a PET study was performed in control and Mdr1a/b(-/-) mice with the overall metabolically most stable tracer [18F]3-d7 (Fig. 4). Increased brain uptake was observed in Mdr1a/b(-/-) mice compared with wild type mice (Fig. 3a). Washout was slow and similar to that of (R)-[11C]verapamil in the brain (Fig. 3b). The ratio in whole brain uptake between Mdr1a/b(-/-) and wild type mice was significantly higher for [18F]3-d7 than for [11C]verapamil (p = 0.0067, paired t-test) (Fig. 3c). This data could be caused by the additional (deuterated) methyl group and consequently difference in log D (1.61 and 2.19 for [18F]2 and [18F]3-d7, respectively (Table 3)), suggesting that the methyl group affects in vivo behavior and (in this case) leads to increased brain penetration in Mdr1a/b(-/-) mice.

Related to the lipophilicity, plasma protein binding could be an important factor for successful clinical implementation of a PET tracer. (R)-[11C]verapamil showed 88% plasma protein binding in human plasma [26], which did not limit its use for imaging. In general, high lipophilic PET tracers show high plasma protein binding [27]. Since all tracers developed are structurally similar to verapamil, but lower in lipophilicity (Table 3), no problems are expected with respect to plasma protein binding. To resolve the true value of the new PET tracer [18F]3-d7, clinical studies are needed. Possible study limitations for translation might be a different route of administration in the clinic, difference in metabolism between species and a laborious precursor syntheses route.

In the present study, no assessment of specificity toward P-gp in comparison with other transporters was performed. However, both (R)-[11C]verapamil and [18F]2 are specific for P-gp, and this is also expected for the structurally similar analog [18F]3-d7.

4. Conclusion

The metabolic stability of existing fluorine-18 labeled verapamil analogs can be improved by inclusion of deuterium in the tracer molecule. In addition, increased metabolic stability of the methyl containing analogs [18F]3-d7 and [18F]3-d7 was observed, which may be the result of steric hindrance of enzymatic metabolism. The similarity in vivo behavior between [18F]3-d7 and (R)-[11C]verapamil, together with improved metabolic stability of [18F]3-d7, compared to the other fluorine-18 labeled tracers, supports the potential of [18F]3-d7 as a candidate for clinical translation as a fluorine-18 labeled PET tracer for evaluation of P-gp.

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Conflicts of interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nucmedbio.2018.06.009.

References


