Introduction

2-Deoxy-2-[18F]fluoro-o-glucose ([18F]FDG) is often referred to as the golden standard in the field of positron emission tomography (PET), where approximately 90% of all PET scans are performed using [18F]FDG. As a glucose derivative, [18F]FDG acts as a biomarker of glucose metabolism and as such has found widespread use in oncology and neurology, both in clinic and in research. When injected into the human body, it preferentially accumulates in tissue that exhibit an increase in glycolysis, e.g., cancer cells. Conversely, diminished glucose consumption due to neuronal cell death in the brain inflected by neurodegenerative disorders, e.g., Alzheimer’s disease, can also indirectly be probed using [18F]FDG. However, despite its prominent role, one major drawback associated with using [18F]FDG is that it suffers from poor tissue selectivity when distinguishing between malignant cells and benign cells that have a high metabolic rate, such as certain cells associated with inflammation or infection. Furthermore, since [18F]FDG is a metabolic imaging agent it is not sufficiently capable of detecting tumors found in most prostate cancers, bronchoalveolar-cell carcinoma or renal-cell carcinoma due to the fact that their metabolic rate is relatively low and therefore indistinguishable from normal tissue. Consequently, there is a great need for new PET tracers that exhibit both high affinity and selectivity towards a particular biomolecular target. In recent years, the concept of employing [18F]FDG as a prosthetic group for the 18F-radiolabeling of ligands with defined molecular targets in vivo has received considerable attention. The rationale is that glycoconjugates (e.g., glycopeptides, glycoproteins) in general exhibit improved pharmacokinetic properties such as increased in vivo kinetics, higher metabolic stability and faster blood clearance compared to their non-glycosylated counterparts. Furthermore, the relatively long half-life of 18F (t1/2 = 109.8 min) provides a sufficient amount of time to perform multi-step radiosynthesis followed by a subsequent PET investigation.

Several methods have been employed for the ligation of [18F]FDG to a diverse set of ligands, for instance (i) via oxime formation, (ii) chemoenzymatic approaches as well as using (iii) thiol-selective S-glycosylation. More importantly, one of the most established methods is by means of the CuAAC click reaction which allows for a wide substrate scope using mild conditions. Accordingly, in 2009, Maschauer et al. reported the synthesis of a set of 2-O-trifluoromethanesulfonyl-o-mannopyranosides, i.e., precursors of [18F]FDG analogs, that were equipped with either a α-1-0-propargyl (10z), α-1-0-(2-azido)ethyl (6α), α- or β-azido aglycons (16α and 16β) respectively, Scheme 1.

In their study, only minor amounts of the α-configured precursors were radio labelled (≤14% radiochemical yield (RCY)) which rendered them inappropriate for PET. In contrast, the β-azido precursor (16β) gave a significantly higher RCY (71%) indicating that the β-anomeric configuration is a key criterion for a successful 18F-radiolabelling.
The propensity of the precursors to undergo the displacement by $^{18}$F correlates well with the Richardson–Hough rules from 1967 that predict the $S_N2$ displacement viability in carbohydrate sulfonate derivatives with external nucleophiles. The outcome of the reaction is dictated by stereoelectronic effects but also accompanied by steric factors. This theory recently got extended by Hale et al. to encompass seemingly disallowed trifluoromethanesulfonate displacements. Briefly, the theory predicts that 2-O-trifluoromethanesulfonyl-$\beta$-D-mannopyranosides experience a significantly lower dipolar repulsion at the transition state and will therefore readily undergo the $S_N2$ displacement while the corresponding $\alpha$-anomer should only give minor substitution or none at all.

The $\beta$-azide equipped $[^{18}$F]$FDG$ (17b, Scheme 1) has successfully been utilized as a $^{18}$F-fluoroglycosylation tool to provide $[^{18}$F]$FDG$ conjugates with a diverse set of ligands, e.g., the RGD peptide targeting the integrin receptor,\textsuperscript{16,17} folic acid targeting the folate receptor,\textsuperscript{18} and a diarylpyrazole targeting the NTS-1 neurotensin receptor.\textsuperscript{19} However, the first generation of clickable $[^{18}$F]$FDGs$ is rather limited in scope. Ideally, a spacer between the $FDG$ unit and the attached click functional group is desired to prevent any potential steric interference between the $FDG$ unit and the ligand to which it will be attached. In fact, it has been shown that glucose derivatives bearing an anomic 1,2,3-triazole, generated from the corresponding glucosyl azide, lack two key properties of $[^{18}$F]$FDG$, \textit{i.e.}, trapping via O-6 phosphorylation and cell uptake via GLUT-1 transporters.\textsuperscript{20} This effect is most likely caused by the close proximity of the triazole. Moreover, ideally, in order to be radiolabel the full set of available click-enabled ligands, both azide- and alkyne equipped $[^{18}$F]$FDGs$ should be accessible. However, to date no alkyne equipped $[^{18}$F]$FDG$ that can be retrieved in a sufficient radiochemical yield is available.

In this work, we report the detailed synthesis of the CuAAC clickable $\beta$-configured $[^{18}$F]$FDGs$ (Scheme 1). In order to evaluate their clickability, the $[^{18}$F]$FDGs$ were chemically ligated to the suitably functionalized Fmoc-protected amino acids Fmoc-$N$-(pro-pargyl)-glycine and Fmoc-3-azido-L-alanine by means of the click reaction which successfully provided the expected $[^{18}$F]$FDG$ conjugates, both rapidly and in good radiochemical yield. Due to the increased cell proliferation of most cancers, protein synthesis is up-regulated and, as a natural consequence, the amino acid uptake is usually significantly increased. The synthesized $[^{18}$F]$FDG$ amino acid conjugates will therefore serve as the basis for a new class of highly promising metabolic imaging agents. Furthermore, the described $^{18}$F-fluoroglycosylation method may well be extended to encompass the radiolabeling of, not only amino acids, but also peptides and proteins.

**Results and discussion**

Since the fluorination step required to obtain the $\beta$-configured $[^{18}$F]$FDG$ ($[^{18}$F]$7$, $[^{18}$F]$11$), is accompanied by an $S_N2$ inversion, the triflate precursors ($6$, $10$) are by necessity $\beta$-$\sigma$-mannopyranosides. Unfortunately, $\beta$-$\sigma$-mannopyranosides are well-known to be challenging to synthesize due to the inherently strong preference of conventional mannosyl donors to form $\sigma$-$\sigma$-mannopyranosides. This is a result of the simultaneous occurrence of both the $\sigma$-directing anomeric effect and repulsion between the axial C-2 substituent and the approaching nucleophile.\textsuperscript{21} Moreover, neighboring group participation of a 2-acyl mannosyl donor...
also leads to α-mannopyranosides. Fortunately, several ingenious synthetic approaches to circumvent these obstacles have already been devised.

A particularly elegant approach was developed by the Danishefsky group during the 1990’s, where epoxidation of peri-benzylated α-glucal using DMDO, conveniently provided the corresponding 1,2-α-anhydrosugar that subsequently during glycosylation stereoselectively produced the corresponding β-D-glucoside – and simultaneously generated an unprotected hydroxyl group in the 2-position. Subsequent epimerization of this site, following an oxidation–reduction sequence generated the β-α-mannopyranoside. In this report we employ a similar synthetic approach which is depicted in Scheme 2. The chosen route requires access to multi-gram quantities of 1,2-anhydrosugar that subsequently during glycosylation stereoselectively produced the corresponding β-D-glucoside – and simultaneously generated an unprotected hydroxyl group in the 2-position. Subsequent epimerization of this site, following an oxidation–reduction sequence generated the β-α-mannopyranoside.

To circumvent these drawbacks, the Dondoni group, in 2006, developed an epoxidation method for glycals where DMDO was used. This protocol was further elaborated on by Lafont et al. in 2011 by the addition of the phase transfer catalyst, tetrabutylammonium hydrogen sulphate (TBAHSO₄) that significantly increased the reaction speed as well as the reproducibility. By employing the oxone-acetone-TBAHSO₄ epoxidation protocol, we conveniently prepared the 1,2-anhydrosugar 2x which was then directly used in the subsequent glycosylation. The glycosylation of 2-chloroethanol or propargyl alcohol, promoted by ZnCl₂ in DCM, provided the corresponding β-D-glucosides 3 and 8 in 39% and 29%, respectively over two steps. The predominant by-product formed was the corresponding 1,2-diol hydrolysis product. Converting the 2-chloroethanol glucoside 3 to the corresponding 2-azidoethyl glucoside 4 proved to be a major challenge. Standard conditions for azidation, i.e., NaN₃ in DMF at elevated temperatures (80 °C or 110 °C), with or without the additives TBAI or TBAB, consistently resulted in a complex mixture of products due to acetate migration to the unprotected 2-ΟΗ, whereas no reaction occurred at ambient temperature. We therefore reasoned that installing a better leaving group might make the reaction proceed more smoothly and thus avoid the accompanying acetate migration. This was realized by converting the 2-chloro compound 3 to the corresponding iodo compound by means of the classical Finkelstein reaction utilizing NaI (2 eq.) in acetone at 70 °C for 48 h. The azidation of the iodoethyl glucoside using NaN₃ in DMF now proceeded cleanly at ambient temperature to afford the azidoethyl glucoside 4 in good yield (77%) over two steps. Next, we decided to use the nitrite-mediated Lattrell–Dax inversion for the pending epimerization. The Lattrell–Dax inversion has been extensively studied by the Ramström group who concluded that the inversion proceeds reliably – and even stereospecifically – if and only if a vicinal equatorial ester is present. This criterion is suitably met for the glucosides 4 and 8. Standard triflation of glucoside 4 using triflic anhydride followed by inversion using TBANO₂ in toluene at ambient temperature over night yielded the β-D-mannopyranosides 5 and 9 cleanly albeit in a moderate yield of 46% and 48% respectively. The β-anomeric configuration was confirmed by evaluating the $J_{C-1,H-1}$ coupling constant in a coupled $^1$H–$^13$C NMR experiment and was found to be 157.6 Hz and 159.0 Hz respectively for β-D-mannopyranosides 5 and 9. With the desired β-D-mannopyranosides at hand, standard triflation afforded the β-D-mannosyl triflates, i.e., the $[^{18}$F]FDG precursors 6 and 10 in 48% and 60%, respectively after silica gel chromatography. Subsequently, to afford the FDG analogs as a non-radioactive reference, a typical fluorination protocol using potassium fluoride and the cryptand kryptofix [K[2.2.2]] in MeCN at 85 °C was attempted. Unfortunately, only trace amount of the expected fluorosugar could be observed, most likely as a result of the known poor nucleophilicity of the fluoride ion. Instead, we choose to directly fluorinate the β-D-mannopyranosides bearing a free hydroxyl-group in the second position, 5 and 9, using the common fluorination agent, DAST. At first, the reaction was run in DCM at −25 °C to rt over night to give the fluorosugars 7 and 11 in 31% and 19% respectively. The poor yield rendered us to instead perform the
reaction in diglyme at 100 °C for 10 min which afforded the fluorosugars 7 and 11 in a significantly increased yield of 66% and 35% respectively. The fluorination proceeded as expected with inversion of configuration, as proven by the characteristic $J_{H-1,H-2}$ coupling constant of 7.6 Hz for 7 and 7.7 Hz for 11, confirming the gluco-configuration. Furthermore, 1D $^{19}$F-NMR revealed a characteristic FDG signal for fluorosugar 7 at $-199.7$ ppm ($dd$, $J_{H-2,F-2} = 50.5$ Hz, $J_{H-3,F-2} = 14.3$ Hz, $J_{H-1,F-2} = 2.7$ Hz), and a similar signal for 11 (ESI,† page 35 and 50 respectively).

To test our hypothesis that a β-configured FDG precursor is radiolabeled to a greater extent than its α-anomeric counterpart, we decided to synthesize the α-FDGs reported by Maschauer et al. to make a direct side-by-side comparison using the same $^{18}$F-fluorination set-up. On closer inspection of our devised synthetic route to the β-FDGs we realized that since the epoxidation step is only moderately stereoselective on acetylated glycals (α/β approx., 7:1),$^{24}$ as a consequence, the minor β-1,2-anhydrosugar (2β) would then upon glycosylation stereoselectively be ring-opened to give the sought α,β-mannopyranosides, 4β and 8β, with the second hydroxyl group exposed.

As predicted, the glycosylations outlined in Scheme 3 resulted in a diastereomeric mixture of the glycosides 4 and 4α, and 8 and 8α, (dr ~ 9:1 gluco/manno in both cases) that were separated using preparative HPLC. Spectroscopic data for the α-mannopyranosides was in good agreement with the data reported by Maschauer et al.$^{20}$ Triflation or fluorination (vide supra) of the isolated α-mannopyranosides then furnished the required precursors (6α and 10α) and the α-configured FDGs (7α and 11α) respectively.

**18**F-Radiolabeling

$^{18}$F was produced using the $^{18}$O(p,n)$^{18}$F reaction using a scanditronix MC-17 cyclotron. The water was transported to the hot cell and trapped on a QMA which was flushed with MeCN. $^{[18]}$F-Fluoride was eluted using a kryptofix 2.2.2/K$_2$CO$_3$ solution. After azeotropic distillation with MeCN the precursor (6, 6α, 10 or 10α) in dry MeCN was added to the vial which was heated to 85 °C for 30 minutes. After the reaction was finished, an aliquot was taken and analysed by radio-HPLC to determine the non-isolated product of the reaction (Table 1). Both β-mannopyranosides 6 and 10 performed well under these conditions and gave RCY of 77 ± 2% and 88 ± 5% for $^{[18]}$F7 and $^{[18]}$F11, respectively (n = 2 for both compounds) (Scheme 4). Unfortunately the α-precurors gave no results (0% RCY) using these conditions as only unreacted $^{[18]}$F- could be identified using analytical radio-HPLC.$^{‡}$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Precursor</th>
<th>Product</th>
<th>RCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>$^{[18]}$F7</td>
<td>77 ± 2</td>
</tr>
<tr>
<td>2</td>
<td>6α</td>
<td>$^{[18]}$F7α</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>$^{[18]}$F11</td>
<td>88 ± 5</td>
</tr>
<tr>
<td>4</td>
<td>10α</td>
<td>$^{[18]}$F11α</td>
<td>0</td>
</tr>
</tbody>
</table>

‡ In the original radiolabelling procedure by Maschauer et al. an optimized kryptofix 2.2.2 buffer (K$_2$CO$_3$/KH$_2$PO$_4$) was necessary in order to keep the precursors intact and obtain a RCY. In addition, the precursor load was 15 μM compared to 2 μM used herein. These differences may explain the failed radiolabelling of the α-precurors in our hands.
Having established a synthetic protocol to acquire the [18F]FDGs we then turned to investigate their performance in the click reaction. We choose to use the appropriately functionalized Fmoc-protected amino acids, Fmoc-N-(propargyl)-glycine (12) and Fmoc-3-azido-L-alanine (14) as a model system to show the proof of concept. The click reaction was performed in a one pot, two-step process starting from [18F] and 6 or 10. After the reaction, the MeCN was evaporated with a stream of helium after which the protected [18F] or [18F] was subsequently dissolved in dry DMF, where the Cu(Ⅰ) catalyst, prepared in situ by the addition of aq. CuSO₄ (50 µL, 0.20 M) and aq. (+)-sodium ascorbate (50 µL, 0.60 M), 60 °C, 20 min, DMF.

**Conclusions**

We have developed a chemoselective 18F-fluoroglycosylation method for PET in vivo imaging that employ the β-configured [18F]FDGs, [18F]7 and [18F]11, as CuAAC clickable prosthetic groups for 18F-labeling. These clickable [18F]FDGs may in principle be readily attached to any click functionalized ligand and thus provide access to a diverse set of 18F-fluoroglycosylated PET radiotracers. We have also demonstrated that the anomeric configuration of the [18F]FDG precursors has a great impact on the radiochemical yield, where the β-configuration is superior to the α-configuration. Furthermore, the clickability of these [18F]FDGs was demonstrated by click coupling to the suitably functionalized Fmoc-protected amino acids, Fmoc-N-(propargyl)-glycine (12) and Fmoc-3-azido-L-alanine (14) in near quantitative RCY, using a simple two-step one-pot protocol. The 18F-fluoroglycosylated amino acids, [18F]13, [18F]15, constitute a new and interesting class of metabolic oncoligic PET radiotracers. We also recognize that while 18F is excellently suited for PET imaging, the natural isotope, 19F, has almost optimal properties for 19F-NMR, a technique that in recent years has received considerable attention as a means to probe biological mechanisms. The developed 18F-fluoroglycosylation method at hand may thus equally well serve as a means to provide novel 19F-NMR probes. Our lab is currently engaged in synthesizing [18F]FDG conjugates targeting cancer and disease associated protein aggregates that will be reported in due course.

**Acknowledgements**

Our work is supported by the Swedish Foundation for Strategic Research and the Swedish Research Council.

**References**