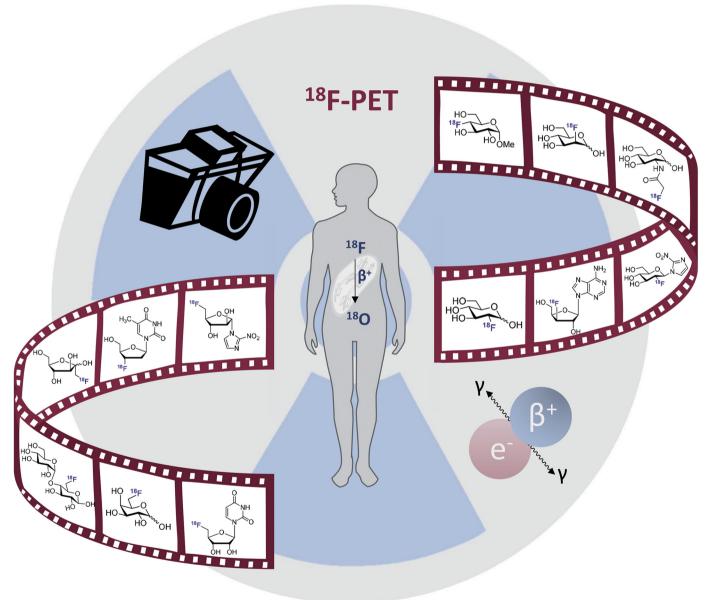
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# Fluorinated carbohydrates for <sup>18</sup>F-positron emission tomography (PET)

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Carbohydrate diversity is foundational in the molecular literacy that regulates cellular function and communication. Consequently, delineating and leveraging this structure–function interplay continues to be a core research objective in the development of candidates for biomedical diagnostics. A totemic example is the ubiquity of 2-deoxy-2-[<sup>18</sup>F]-fluoro-p-glucose (2-[<sup>18</sup>F]-FDG) as a radiotracer for positron emission tomography (PET), in which metabolic trapping is harnessed. Building on this clinical success, more complex sugars with unique selectivities are gaining momentum in molecular recognition and personalised medicine: this reflects the opportunities that carbohydrate-specific targeting affords in a broader sense. In this Tutorial Review, key milestones in the development of 2-[<sup>18</sup>F]-FDG and related glycan-based radiotracers for PET are described, with their diagnostic functions, to assist in navigating this rapidly expanding field of interdisciplinary research.

#### **Key learning points**

- (1) 2-[18F]-FDG has been the gold standard PET tracer since the 1980s, but its lack of specificity limits clinical application.
- (2) The structure-activity profile of 2<sub>[</sub><sup>18</sup>F]-FDG is instructive to design blueprints for future carbohydrate tracer development.
- (3) Judicious selection of the carbohydrate core can enable increased specificity over 2-[18F]-FDG for individual disease cases.
- (4) The site and configuration of the <sup>18</sup>F-radiolabel provides a handle to modulate biological uptake and function.

# 1. Introduction

Advancing the field of personalised medicine is contingent on the development of effective diagnostic platforms to guide precision therapies.¹ In the current suite of non-invasive imaging methods, positron emission tomography (PET) has emerged as a key enabling technology to investigate anatomy and metabolic function:² this provides a powerful impetus to expand the existing repertoire of tailored PET tracers to meet the clinical demand. Of the existing small molecule portfolio, the ¹8F-fluorinated monosaccharide, 2-deoxy-2-[¹8F]-fluoro-pglucose (1) (2-[¹8F]-FDG or [¹8F]FDG),³-6 is most broadly utilised, and largely responsible for the transformative success of PET worldwide. Grounded in the translational efficacy of fluorine bioisosterism *in vivo*, <sup>7-11</sup> this exemplar of molecular mimicry enables cellular glycolysis to be expropriated thereby

ensuring that 2-[18F]-FDG (1) reaches metabolically upregulated cells. In contrast to native p-glucose (2), OH → <sup>18</sup>F substitution at C2 prohibits further cell metabolism, thereby ensuring accumulation of the radiotracer. 12 Upon decay, positron emission occurs relatively quickly ( $t_{1/2}$  = 109.8 minutes to generate <sup>18</sup>O) and in a highly localised environment. The annihilation event resulting from collision of a positron and an electron produces γ-rays, which are emitted in a 180° relationship: these  $\gamma$ -rays can be reconstituted thereby providing clinicians with detailed topographical information about the affected tissue. Buoyed by the clinical impact of 2-[18F]-FDG (1), a broad spectrum of specialised carbohydrate-based radiotracers has been established for applications in nuclear medicine. <sup>13</sup> In this Tutorial Review, a systematic, structure-based overview of <sup>18</sup>F-modified sugars is disclosed together with relevant physico- and radio-chemical data. This classification strategy is intended to provide a practical structure-function guide to carbohydrate-based radiotracer development and stimulate further interest in this cornerstone of personalised medicine.

The diagnostic paradigm of PET has its origins in the early work Kuhl, Chapman and Edwards in the late 1950s (Fig. 1A).<sup>14</sup> Tomography imaging by Ter-Pogossian and Phelps followed, <sup>15,16</sup> and the rapid growth of the field, including the

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introduction of the single plane PET instrument, culminated in the validation of the circular transverse positron camera. 17,18 These technological advances fuelled the search for suitable synthetic (radiolabeled) molecules that would facilitate full body imaging: a seminal advance was the validation of <sup>14</sup>Cdeoxyglucose in autoradiography. 19 This culminated in the discovery of one of the most important diagnostic compounds of the last century, 2-[18F]-FDG (1) (Fig. 1B). Following the synthesis of the (cold) <sup>19</sup>F counterpart 2-FDG, <sup>20</sup> the synthesis of (hot) 2-[18F]-FDG (1) was first reported by Wolf and coworkers in 1978.21 Clinical translation of this tracer was contingent on establishing that 2-[18F]-FDG (1) was an acceptable substrate for hexokinase, and that metabolic trapping occurred (i.e. further glycolysis was paused). Since these conditions were



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Emma Campbell was born in the Isle of Lewis (Scotland) in 1992. She completed her MSci degree in Chemistry with Medicinal Chemistry from the University of Glasgow under the direction of Dr Joëlle Prunet in 2017. She went on to receive her PhD in Pure and Applied Chemistry from the University of Strathclyde under the supervision of Prof. Glenn A. Burley working on the design of small molecules to modulate RNA splicing. Following her PhD, she

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met, tissue accumulation occurred thereby rendering 2-[18F]-FDG (1) an excellent candidate for D-glucose transport imaging.<sup>22</sup> Since its conception and introduction to the clinic, 2-[18F]-FDG (1) has revolutionised in vivo PET imaging: this has been summarised (up until 2001) in an excellent review by Gambhir et al.<sup>23</sup>

The parallels between PET imaging and photography are striking, but in the former case the 3D-camera is reliant on gamma rays emitted from the point of interest within the body, rather than light. The generation of this gamma signature is conditional on injection of a radiotracer (in this case <sup>18</sup>F) into the patient and subsequent efficient distribution (Fig. 1C). In the case of 2-[18F]-FDG (1), accumulation is a consequence of molecular editing with fluorine in which a subtle, bioisoteric OH to F replacement suppresses glycolysis. Subsequent  $\beta^+$ decay converts the radioisotopic <sup>18</sup>F to <sup>18</sup>O by emitting both a neutrino (n) and a positron ( $\beta^+$ ). The latter species is short lived and, upon collision with an electron, undergoes an annihilation event with the emission of two photons of equal energy (511 keV each) in a 180° angle. The recurring emission can be detected and reconstituted to construct a 3D image that conveys the origins of positron emission. Moreover, the ultimate decay of the <sup>18</sup>F of 2-[<sup>18</sup>F]-FDG (1) to <sup>18</sup>O ensures that, upon protonation, native p-glucose (2) is generated and the conventional glycolysis pathway continues (Scheme 1). Generating Dglucose (2) as the sole metabolite of 2-[18F]-FDG (1) injection, coupled with the low molar activities used in PET, mitigates concerns pertaining to side effects and enables diagnostic information to be gleaned by pausing a cellular process.

Application of 2-[18F]-FDG (1) as a diagnostic tool has proven to be expansive owing to the importance of D-glucose (2) as a cellular energy source and the metabolic disparity that differentiates healthy and abnormal cells. Pioneering work by



Christina Jordan

studied Christina **Jordan** chemistry at the University of Münster and completed her bachelor studies in 2016 in the field of medicinal chemistry working on the synthesis of antagonists. receptor During her master studies, she decided to focus on synthetic organic chemistry and joined the group of Prof. Ian Fairlamb at the University of York studying replacement in C-H activation. Thereafter, she started working

with Prof. Ryan Gilmour in 2018 for her master thesis in the field of carbohydrate chemistry. After an internship at the Bayer AG in Wuppertal, Christina moved back to Prof. Ryan Gilmour's lab to do her PhD. Her research focuses on the synthesis of fluorinated carbohydrates for vaccine development.



Ryan Gilmour

Ryan Gilmour was born (1980) in Ayrshire, Scotland and educated at the University of St Andrews, where worked with Prof. David O'Hagan FRSE. He received his PhD from the University of Cambridge working under the direction of Prof. Andrew B. Holmes FRS. Following postdoctoral research fellowships at Max-Planck-Institut für Kohlenforschung (with Prof. A. Fürstner) and the ETH Zürich (with Prof. P. H. Seeberger) he

was appointed as Alfred-Werner-Assistant-Professor at the ETH (2008-2012). He is currently Chair of Organic Chemistry and CiMIC Professor of Chemical Biology at the Westfälische Wilhelms-Universität Münster (Germany). Gilmour is a Fellow of the Royal Society of Chemistry (2015) and a Corresponding Fellow of the Royal Society of Edinburgh (2021).

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A В Kuhl. PC-I: first First PET-CT scanner 2-deoxy-Cardiology Chanman and [18F]FDG prototype installed at instrument Uni. Pittsburgh Med Edwards using 2D developed as propose PET arravs PFT tracer Centre Oncology 1970 2000 2010 1950 1980 1990 Inflammation 18F-FDG 1 Infectious Disease <sup>14</sup>C-Deoxyglucose Development of the PET-CT 18F major functions: plane PET (DG) developed circular transverse [18F]FDG scanners Inhibition of hydrolysis and investigated axial positron available Radionucleus with relatively long by FDA half-life  $t_{1/2}$  = 109.8 mins 18O 8P+10N 3D detection by  $= 1P = 1n + 1N + 1n^{4}$ v-cameras enables localisation of B+-decay origin

Fig. 1 (A) Timeline of key historical milestones in the development of positron emission tomography (PET). (B) Schematic of 2-1<sup>18</sup>FJ-FDG (1) and its use in various diagnostic fields. (C) Timeline of PET analysis: intravenous injection of a patient with <sup>18</sup>F labelled radiotracer. The radiotracer accumulates in the target cell as it cannot be fully metabolised due to the presence of the  $C(sp^3)$ -F (metabolic trapping), and subsequently decay to <sup>18</sup>O (through  $\beta^+$  decay) is observed. Collision with a positron results in the emission of  $\gamma$ -rays in a 180° angle. The  $\gamma$ -rays are detected by a circular 3D  $\gamma$ -cameras allowing an image to be generated

18F decays to 18O under B+ decay

Warburg and Minami in the early 1920s laid the foundations for the venerable "Warburg effect": the phenomenon that high levels of anaerobic glycolysis is observed in tumour cells.<sup>24,25</sup>

Radiotracer accumulates

in pathoaenic cell

Injection of radiotracer

into Patient

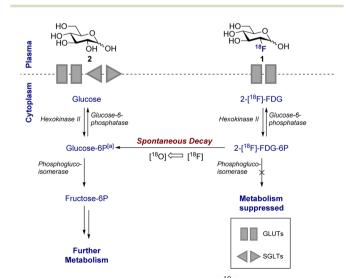
Warburg subsequently received the 1931 Nobel Prize in Physiology for Medicine "for his discovery of the nature and mode of action of the respiratory enzyme". An example of the effectiveness of 2-[18F]-FDG PET/CT in visualising esophageal squamous cell carcinoma is shown in Fig. 2.

This disparity in metabolic phenotypes can be leveraged to distinguish tumour cells in vivo by PET imaging.26,27 In the conventional glycolysis pathways, the internalisation of D-glucose (2) into the cell is regulated by two D-glucose transporters (GLUT-1 and GLUT-3), which then enables subsequent phosphorylation by the enzyme hexokinase II (HK-II). 22,27 The phosphorylated p-glucose (Glucose-6P) is then isomerised to fructose-6P, enabling further metabolism (Scheme 1). The molecular mimic, 2-[18F]-FDG (1), initially participates in the same uptake process, but subsequent glycolysis is paused by fluorine substitution at the C2-OH. This single atom edit is not compatible with phosphogluco-isomerase, leading to trapping and accumulation of <sup>18</sup>F-labelled p-glucose within the cell. It is interesting to note that any remaining 2-[18F]-FDG (1) which is not phosphorylated to 2-[18F]-FDG-6-P by the hexokinase is excreted: this lowers the background signal which, in turn, improves the image resolution.<sup>28</sup> Furthermore since glucose-6phosphatase, which regulates dephosphorylation, is underexpressed in tumour cells, tracer accumulation is further amplified.29

The mechanism of accumulation is multifaceted and may be considered as a combination of p-glucose metabolism, hexokinase and D-glucose-6-phosphate activity, and the excretory pathway through the urinary tract. Despite this complexity, 2-[18F]-FDG (1) uptake is known to be proportional to p-glucose consumption.

B+ combines with e- under v-ray

emission (annihilation)



Scheme 1 Schematic of p-glucose versus 2-[18F]-FDG metabolism. Key shows which transport proteins facilitate cellular uptake. [a] Decay of 2-[18F]-FDG produces D-glucose-6P with a heavy 18O in the 2-position.

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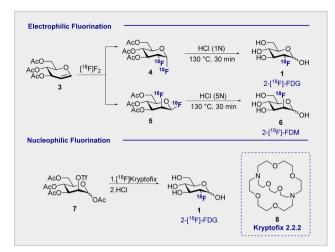
Fig. 2 <sup>18</sup>F-FDG PET/CT fusion image of esophageal squamous cell carcinoma in a 68-years-old woman. The SUV of the tumour was determined to be 3.75 and the metabolic tumour volume was 0.155 m<sup>-1</sup>. This research was originally published in Radiation Oncology: L. Xia, L., X. Li., J. Zhu, Z. Gao, J. Zhang, G. Yang, Z. Wang, Prognostic value of baseline <sup>18</sup>F-FDG PET/CT in patients with esophageal squamous cell carcinoma treated with definitive (chemo)radiotherapy. Radiat. Onco., 2023, 18, 41. Reused under the Creative Commons Attribution 4.0 International License (https:// creativecommons.org/licenses/by/4.0/).

Collectively, the introduction of the 18F-label at the 2position of p-glucose serves two principal functions: (i) it mimics the natural abundance isotope, 30 thereby inhibiting Dglucose metabolism and facilitating accumulation in affected cells, and (ii) it serves as an imaging probe to study organ dysfunction. Deconstructing and harnessing this unique, structure-specific mechanism (vide infra) enables an array of cancer pathologies to be imaged as well as providing a platform investigating p-glucose metabolism, kinetics inflammation.

# 2. Synthetic routes to 2-[18F]-FDG: a brief history

# 2.1 Electrophilic fluorination

Functional small molecule validation is a powerful driver of synthetic innovation and the validation of 2-[18F]-FDG (1) in the context of PET is no exception. Early synthetic routes to these fluorinated monosaccharides relied on direct electrophilic fluorination of 3,4,6-tri-O-acetylglucal with hazardous elemental fluorine, followed by global hydrolysis using HCl. 4,31 Although successful, this protocol furnished 2-[18F]-FDG (1) and 2-deoxy-2-[18F]fluoro-D-mannose (6) (2-[18F]-FDM) in a 3:1 ratio (Scheme 2, upper). Fuelled by increasing demand for the radiotracer, a re-evaluation of the initial synthesis routes was required to accommodate the short half-life of the <sup>18</sup>F isotope  $(t_{1/2} = 109.8 \text{ min})$ . Whilst the half-life does permit limited synthetic manipulations to be conducted, the separation of



Scheme 2 <sup>18</sup>F Fluorination methods: (upper) electrophilic fluorination produces both 2-[18F]-FDG (1) and 2-[18F]-FDM (6) products; (lower) nucleophilic fluorination produces solely glucose-configured 2-[18F]-FDG (1).

diastereoisomeric mixtures represented a major bottleneck in production that required attention. Although the exploration of reagents such as [18F]-acetyl-hypofluorite led to an improvement in yield and selectivity (95% yield of the glucose tracer),  $^{32,33}$  the radiochemical yield (RCY = 24  $\pm$  3%) remained low.34

#### 2.2 Nucleophilic fluorination

Electrophilic paradigms proved essential in generating 2-[18F]-FDG (1) for early studies in mice, dogs and humans, and remained indispensable for two decades after the first synthesis was reported.3,5

However, the introduction of Kryptofix<sup>®</sup> [2.2.2] (8) to generate 2-[18F]-FDG (1) by nucleophilic displacement of the D-mannose-derived triflate by Hamacher et al. proved transformative (Scheme 2, lower).35 Whilst conceptually related nucleophilic approaches had already been communicated, a series of synthetic limitations remained unresolved, particularly poor deprotection or 18F incorporation.36,37 The addition of Kryptofix<sup>®</sup> [2.2.2] (8) was found to enhance fluoride nucleophilicity and, by extension, <sup>18</sup>F incorporation. <sup>38</sup> Under optimised conditions, the fluorination of 1,3,4,6-tetra-O-acetyl-2-Otrifluoromethanesulfonyl-β-D-manno-pyranose (7), followed by global deprotection using HCl, enabled 2-[18F]-FDG (1) to be generated with an uncorrected yield of 44  $\pm$  4% (Scheme 2). 35 Acidic hydrolysis with HCl, classically requiring elevated temperatures and longer reaction times, can be achieved at room temperature under basic conditions. This further circumvents complications arising from nucleophilic displacement frequently observed in acidic conditions. It is pertinent to note that production efficiency remains a significant contributor to the clinical success of 2-[18F]-FDG (1), which received FDA approval in 1999.39 Following the transformative success of Kryptofix<sup>®</sup> [2.2.2] (8) in nucleophilic radiofluorination protocols, the next 15 years of process development focussed heavily

on the evaluation of alternative <sup>18</sup>F sources, improving deprotection efficiency and identifying impurities. 40,41 It wasn't until the early 2000s that the radiofluorination repertoire was augmented to include enzymatic fluorination.

#### **Enzymatic fluorination**

In advancing the field of nucleophilic fluorination for PET, particularly in a clinical environment, post-reaction radiotracer isolation is a conspicuous consideration. The use of conventional organic solvents to enable fluorination must be reconciled with the need for aqueous solutions of the tracer to enable injection into the patient. Translating nucleophilic radiofluorination to an enzymatic paradigm would enable fluoride production, and C(sp3)-18F bond formation to be executed in the same aqueous phase, thereby significantly shortening operational times. In a seminal study, Prante and co-workers demonstrated the potential of this approach by coupling pre-labelled 2-[18F]-FDG (1) and UDP-2-[18F]-FDG using UDP-glucosephosphorylase (EC 2.7.7.9, bovine liver).<sup>42</sup> In the absence of a biocatalyst able to facilitate C-F bond formation, the application of enzymatic radiofluorination in PET seemed set to be restricted to transformations involving pre-fluorinated substrates. However, the isolation of 5'-fluorodeoxyadenosine synthase from Streptomyces cattleya by O'Hagan and coworkers proved to be a transformative event in organofluorine chemistry, 43,44 and biocatalysis in a broader sense. 45 The discovery of this first "fluorinase" not only allowed the biosyntheses of rare organofluorines to be rationalised, 46,47 but it afforded unrivalled opportunities for the production of biomedically important materials. 47-49 A totemic example of enzymatic radiotracer synthesis from the laboratories of Martarello and O'Hagan was the synthesis of radiolabelled 5'-deoxy-5'-[18F]-fluoroadenosine (10) (5'-[18F]-FDA) from commercially available S-adenosyl-methyltransferase (9) (SAM) in a RCY of up to 95% (Scheme 3).50,51 This remarkably high RCY was achieved through biasing the equilibrium of the reaction

**Enzymatic Fluorination**  $NH_3$ Fluorinase 5'-[<sup>18</sup>F]-FDA 1. PNP, PO4 5'-[18F]-FDU

Scheme 3 Enzymatic <sup>18</sup>F fluorination enzyme to produce 5'-[<sup>18</sup>F]-FDA. 5'-[18F]-FDA can be further derivatised with PNP to produce 5'-[18F]-FDU.

towards the product by judicious addition of L-amino acid oxidase (L-AAO). This addition of the second enzyme ensured that the by-product, L-methionine (11) was processed to the 2oxo acid (12), thereby preventing the reverse reaction to regenerate the starting material. This enzymatic platform has been improved by over-expression of the gene encoding the catalyst in Escherichia coli. Enzymes are, in general, limited by their substrate specificity, however coupling with subsequent enzymes to affect downfield transformations (purine nucleoside phosphorylase (PNPs) and thymidine phosphorylases (TPs)), can broaden the scope immensely. Although biocatalysis-based fluorination strategies are highly appealing, leveraging this technology for clinical production remains in its infancy. A comprehensive survey of this area,52 and of methodological advances in synthetic radiochemistry in a more general sense, 53-56 are beyond the scope of this review. Moreover, advances in modern automation approaches for the GMP clinical production of 2-[18F]-FDG (1) are discussed elsewhere. 57-62

### 2.4 Exploring the stereochemical etiology of 2-deoxy-2-[18F]fluoro-D-glucose (2-[18F]-FDG) effectiveness

The clinical validation of 2-[18F]-FDG (1), coupled with the relative stereochemical complexity of monosaccharides in general, continues to provide a strong foundation for the design and evaluation of structural analogues (vide infra). As it is illustrated in Fig. 3, many common hexoses are related by site-selective epimerisation at the C2 and/or C4 positions such that simple editing provides a handle to modulate the physicochemistry and function of the tracer. The effects of these seemingly subtle modifications often manifest themselves in human metabolism which, by extension, can be leveraged for diagnostic purposes: a pertinent example is the D-glucose (2), Dgalactose (16), D-mannose (15) series.

Whilst D-mannose (15) and D-galactose (16) both occur frequently in nature and are important nutritional components, D-galactose (16) is particularly noteworthy as it can serve as a D-glucose (2) substitute, due to preferential consumption in

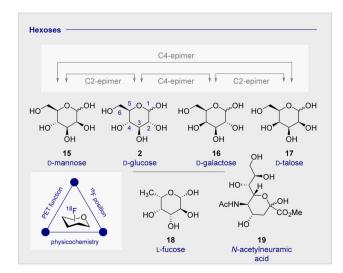


Fig. 3 The relative configuration of selected monosaccharides.

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the brain and associated insulin-independence. 63 Indeed, studies in Wistar rats treated with streptozoticin have established that long-term oral D-galactose exposure reduces cognitive decline.64 This may have therapeutic implications for the management of neurodegenerative diseases, particularly in Alzheimer's disease where a high proportion of patients experience insulin-intolerance. Consequently, augmenting the small molecule tracer collection by structural editing, including regulatory deoxysugars (e.g. L-fucose (18))65 and neuraminic acid (19) derivatives<sup>66,67</sup> continues to be intensively pursued.

# 3. <sup>18</sup>F-modified monosaccharide tracers

## 3.1 An overview of the current portfolio of 2-[18F]-FDGinspired monosaccharides for PET (Fig. 4)

Continued interest in 2-[18F]-FDG (1) stems not only from its clinical success, but also from a desire to understand the

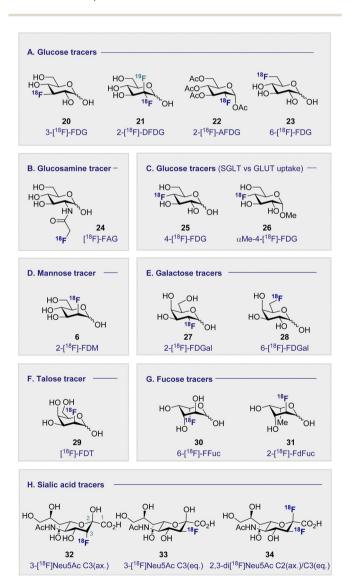


Fig. 4 Structures of selected <sup>18</sup>F monosaccharides.

etiology of related hexoses in the context of PET. An early comparative analysis by Kearfott et al. in 1984 reported the effects of relocating the quasi-equatorial 18F-label by one position to generate 3-[18F]-fluoro-deoxy-D-glucose (20) (3-[18F]-FDG)

Investigations in mice, rats and dogs revealed that 2-[18F]-FDG (1) was consistently superior to 3-[18F]-FDG (20) in the heart, brain and kidneys.<sup>68</sup> Furthermore, tissue retention was found to be higher with 2-[18F]-FDG (1), which is likely due to lower levels of phosphorylation and faster clearance of 3-[18F]-FDG (20) from the blood and kidneys. Regrettably, this unfavorable performance relative to 2-[18F]-FDG (1) has relegated 3-[18F]-FDG (20) from the list of preferred 18F-monosaccharides, and underscores the importance of label positioning in tracer design. Additional fluorination of the 2-[18F]-FDG (1) scaffold, to generate [18F]-2-deoxy-2,2-difluoro-p-glucose (21) (2-[18F]-DFDG) was destined to follow a similar fate. 69 Whilst biodistribution in a Rhesus monkey was comparable to that observed with 2-[18F]-FDG (1), significant uptake in the surrounding muscles compromised the target to background ratio signal, thereby limiting further development of 2-[18F]-DFDG (21). From a preparative standpoint, leveraging globally protected monosaccharides for PET convey a range of advantages: the most notable include physicochemical modulation and the elimination of a time-consuming final deprotection step. In order to enhance the lipophilicity of 2-[18F]-FDG (1), and increase uptake rates, Waki et al. synthesised 1,3,4,6tetra-acetyl-2-[18F]-2-deoxy-D-glucose (22) (2-[18F]-AFDG), and evaluated it in vitro (Fig. 4A).70 In line with their working hypothesis, the authors observed intracellular hydrolysis of 2-[18F]-AFDG (22) to 2-[18F]-FDG (1), and an enhancement in uptake that was "GLUT independent". This study indicates that increasing lipophilicity enables hexokinase activity to be studied independent of GLUT kinetics. The <sup>18</sup>F-hexose library was further expanded in 2005, when Neal et al. reported a p-glucosebased PET tracer with the <sup>18</sup>F-probe installed at the C6-position to study the physiology and pathology of D-glucose transporters (GLUTs).71

Further studies confirmed that 6-[18F]-FDG (23) was transported by GLUTs in a process analogous to D-glucose (2).<sup>72</sup> Collectively, this provided a structural foundation, based on the site of radiofluorination, to investigate two fundamentally different processes: cell entry, and phosphorylation through direct comparison with 2-[18F]-FDG (1). It is interesting to note that 6-[18F]-FDG (23) was found to accumulate predominantly in the brain liver and heart, which is in contrast to kidney accumulation noted with 2-[18F]-FDG (1).72 Since 6-[18F]-FDG (23) was also insulin responsive, and GLUTs are associated with insulin-stimulated diseases, the Muzic laboratory investigated 6-[18F]-FDG (23) as a tracer for p-glucose transport.73 An important finding was the increased concentration of radioactivity observed in skeletal muscle in the presence of insulin. The authors have further corroborated this observation by demonstrating that 6-[18F]-FDG (23) can be leveraged to measure p-glucose transport in vivo in an insulin-resistant rat model.74

#### 3.2 Monosaccharides imaging bacteria (Fig. 4B)

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Commonly used as a dietary supplement, glucosamine is also one of the core units of peptidoglycans, a polysaccharide that creates the bacterial cell wall from alternating units of N-acetylmuramic acid and N-acetylglucosamine. As such, glucosamine could be an interesting target for bacterial imaging. In 1990, a glucosamine analogue, N-[18F]-fluoroacetyl-Dglucosamine (24) ([18F]-FAG) was initially investigated for imaging tumours in mice bearing spontaneous hepatomas.<sup>75</sup> High uptake was observed in the tumour, kidney and liver 60 min post injection (p.i.) with a strikingly highest uptake noted in the tumour at 5.16  $\pm$  0.82% ID per g. Over a decade later, the same compound was evaluated for imaging bacterial infections.<sup>76</sup> Exploitation of glucosamine's ubiquitous presence in the bacterial cell wall structure could be advantageous in distinguishing between bacterial infection and non-bacterial inflammation. A study in Sprague-Dawley rats, whereby inflammation or infection was induced in a localised manner, showed [18F]-FAG (24) selectively imaged bacterial infection over nonbacterial inflammation. By comparison, 2-[18F]-FDG (1) was observed to image both infection and inflammation in a manner that it would be difficult to distinguish between the two. By extension, [18F]-FAG (24) has become a promising tracer for future development, particularly with regards to differentiating bacterial infection and sterile inflammation. Another potential imaging probe for bacterial infection derives from the reduction of 2-[18F]-FDG (1) to generate 2-deoxy-2-[18F]fluorodeoxysorbitol (36) ([18F]-FDS) (Scheme 4).

[18F]-FDS (36) is metabolised by Enterobacteriaceae (Gramnegative bacteria) and not by Gram-positive bacteria or mammalian cells. This difference can be leveraged to enable the targeted imaging of Gram-negative infections. In 2014, a study comparing uptake of [18F]-FDS (36) and 2-[18F]-FDG (1) in Escherichia coli (Gram-negative bacteria), Staphylococcus aureus (Gram-positive bacteria) confirmed uptake of 2-[18F]-FDG (1) in both strains, however uptake of [18F]-FDS (36) was only observed in the Escherichia coli cells.77 In the same study, in vivo experiments in mice injected with both active and inoculated Escherichia coli showed [18F]-FDS (36) accumulation was exclusive to the area injected with the active infection over the sterile inflammation. The tracer was later translated to human clinical studies which showed no adverse side effects from the injection of the tracer after 24 h as well as good clearance through the bladder.78

Scheme 4 The synthesis of  $[^{18}F]$ -FDS (36) by reduction of 2- $[^{18}F]$ -FDG (1).

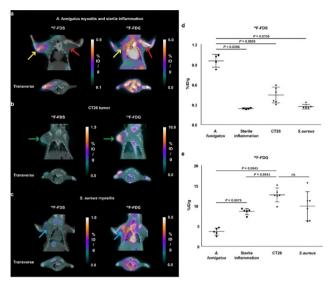


Fig. 5 Comparison of [18F-FDS (36) and 18F-FDG in BALB/c mice. (a) Red arrow: mice injected with sterile inflammation; Yellow arrow: Aspergillus fumigatus-infected myositis. (b) Green arrow: CT26 tumours. (c) Blue arrow: Staphylococcus aureus-infected myositis. (d) [18F]-FDS (36) quantification. (e) 2-[18F]-FDG quantification. This research was originally published in Nature Communications: D. Y. Kim, A. Pyo, S. Ji, S. H. You, S. E. Kim, D. Lim, H. Kim, K. H. Lee, S. J. Oh, Y. Jung, U. J. Kim, S. Jeon, S. Y. Kwon, S. R. Kang, H. B. Lee, H. Hyun, S. Y. Kim, K. S. Moon, S. Lee, S. J. Kang and J. J. Min. In vivo imaging of invasive aspergillosis with 18Ffluorodeoxysorbitol positron emission tomography, Nat. Commun., 2022, 13, 1-11. Reused under the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

More recently [18F]-FDS (36) research has been expanded to include fungal infections, in particular the Aspergillus strain (Fig. 5).<sup>79,80</sup> Initial comparative studies with Escherichia coli showed poor uptake in Aspergillus fumigatus by comparison with the Gram-negative bacteria. In addition, [18F]-FDS (36) accumulation was outmatched by 2-[ $^{18}$ F]-FDG (1) (0.290  $\pm$  0.030 and 8.416  $\pm$  0.964% ID mL $^{-1}$  respectively) in infected lungs. $^{79}$ However, later *in vitro* studies indicated comparable [18F]-FDS (36) uptake in Aspergillus fumigatus, Rhizopus arrhizus and Candida albicans with Escherichia coli.80 When translated to an animal model (immunosuppressed BALB/c mice) visualisation of the infected muscle was significant, with an mean infected muscle to normal muscle ratio of 8.90  $\pm$  1.81 at 2 h.

A comparative study with 2-[18F]-FDG (1) in BALB/c mice highlighted a 3.9-fold higher [18F]-FDS (36) uptake in infected muscle than inflamed tissue (0.95  $\pm$  010% ID per g and 0.24  $\pm$ 0.01% ID per g respectively). 2-[18F]-FDG (1) on the other hand showed higher uptake in the site of sterile inflammation (Fig. 5). Selective uptake for infected tissue over normal tissue was further replicated in the brain and lung, with as a high as 30.7-fold higher uptake in the infected lung tissue over the normal making it a promising diagnostic tool for fungal infections in the future.

#### 3.3 p-Glucose uptake: the GLUT and SGLT pathways (Fig. 4C)

Whilst 2-[18F]-FDG (1) quickly rose to prominence as an indispensable tool for measuring the kinetics of p-glucose

metabolism through the GLUT pathway, this particular structural isomer proved unsuitable for exploring sodium p-glucose co-transporter pathways. The SGLT pathway facilitates absorption of p-glucose through the lining of the small intestine mucosa, where an ATPase biases the Na<sup>+</sup>/K<sup>+</sup> gradient across the proximal tubule cell. This imbalance creates a downhill sodium gradient which can be used by the SLGT proteins to actively transport the p-glucose through the apical membrane. 81-83 Although 2-fluoro sugars have found application as SGLT2 inhibitors, <sup>84,85</sup> 2-[<sup>18</sup>F]-FDG (1) is not a substrate

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for SGLT and as such could not be used to study these proteins via PET.86 Systematic studies have established that the hydroxyl groups at C1, C3 and C6 of D-glucose are required for GLUT uptake, whilst the C4 position is less critical (Fig. 6). In contrast, the C2 and C3 hydroxyl groups are essential for SLGT transport providing a structural foundation to distinguish between these pathways. 87-89 4-[18F]-Fluoro-4-deoxy-D-glucose (25) (4-[<sup>18</sup>F]-FDG) has thus been employed to investigate the physiological roles of SGLTs and GLUTs by PET in mice and found to have a high affinity for SGLTs, whilst also being a substrate for GLUT uptake (Fig. 4C). 87,90 In parallel, the methylated analogue, α-methyl-4-[18F]-fluoro-4-deoxy-p-glucopyranoside (26) (αMe-4-[18F]-FDG), was designed as a SGLT-specific tracer based on previous studies on the methylated p-glucose analogue (aMDG). aMDG was shown to be selective for SGLT uptake over GLUT, 91 (a high affinity substrate for SGLT1 and SGLT2 but not GLUTs)92 and a poor substrate for hexokinase. 22,86 In 2016, as part of a wider study of p-glucose homeostasis, the functional expression of SGLTs and GLUTs was measured in mice by comparative analysis of 2-[18F]-FDG (1) and  $\alpha$ Me-4-[<sup>18</sup>F]-FDG (26). As expected, 2-[<sup>18</sup>F]-FDG (1) produced a signal in the brain, heart and kidneys and was excreted by the bladder. 90 In stark contrast, the study with αMe-4-[18F]-FDG (26) revealed poor brain penetration such that there was no observable signal. Importantly, 4-[18F]-FDG (25) accumulated in the brain but

only in regions where SGLTs are expressed. It is also pertinent to note that  $\alpha Me-4-[^{18}F]-FDG$  (26) is not a substrate for hexokinases and thus it is not accumulated through the GLUT mechanism like 2-[18F]-FDG (1).86

Recently, Wright and co-workers have validated αMe-4-[18F]-FDG (26) as a SGLT specific PET imaging probe in patients with high-grade astrocytoma.<sup>93</sup> In contrast to 2-[<sup>18</sup>F]-FDG (1), which

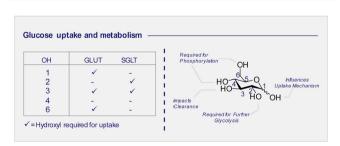


Fig. 6 D-Glucose uptake: hydroxyl groups required to enable GLUT or SGLT uptake (left). D-Glucose metabolism: structure activity profile dictating which positions can be modified for tracer design (right).

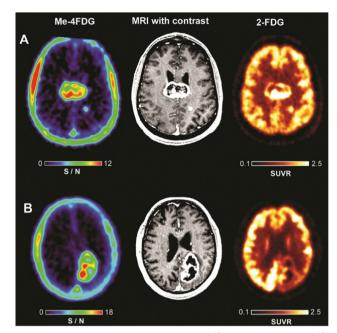


Fig. 7 Comparison of PET imagers αMe-4-[<sup>18</sup>F]-FDG (left) and 2-[<sup>18</sup>F]-FDG (right) with MRI (middle) in WHO Grade IV astrocytoma patients. This research was originally published in the Journal of Neuro-oncology: V. Kepe, C. Scafoglio, J. Liu, W. H. Yong, M. Bergsneider, S. C. Huang, J. R. Barrio and E. M. Wright, Positron emission tomography of sodium Dglucose cotransport activity in high grade astrocytomas, J. Neurooncol., 2018, 138, 557-569. Reused under the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

was broadly distributed in the brain resulting in poor to no resolution, αMe-4-[18F]-FDG (26) accumulated in the tumour with a high ratio to the background signal. Indeed, a mass as small as 6 mm in a grade IV tumour patient was observable. And the imaging was sufficiently resolved to be comparable with gadolinium-based MRI (Fig. 7).

#### D-Mannose-based <sup>18</sup>F radiotracers (Fig. 4D)

No etiological survey of hexoses in personalised medicine would be complete without a comment on the C2-epimer of  $2-[^{18}F]-FDG$  (1): 2-deoxy- $2-[^{18}F]$ -fluoro-p-mannose (6)  $(2-[^{18}F]$ -FDM) (see Scheme 2 and Fig. 4D). A study by Fukada et al. evaluated the properties and activity of 2-[18F]-FDM (6) as a radiotracer in tumour tissue.94 The synthesis of the radiotracer was achieved following the established method for the Direct comparison with 2-[18F]-FDG (1) revealed that both radiotracers displayed a similar high uptake in tumour tissue, and high tumour to tissue ratio was observed across most organs. Furthermore, PET studies performed on a rabbit tumour with 2-[18F]-FDM (6) showed clear distinctions between the diseased tissues, tumour and lymph node metastases.

The synthesis of 2-[18F]-FDM (6) was further optimised through nucleophilic displacement (yield: 50-68%, purity: 97.6-98.7%) in 2013, increasing appeal of 2-[18F]-FDM (6) as a potential tumour imaging agent.95 In vitro studies, in AH109A cells, showed 2-[18F]-FDM (6) had rapid uptake by tumour cells (30 minutes) and that this uptake was sensitive

to co-administration with p-glucose. When studied in AH109A bearing rats, the tumour to muscle ratio was similar to 2-[18F]-FDG (1) (5.30  $\pm$  1.54 and 6.20  $\pm$  1.63 respectively) but 2-[18F]-FDM (6) had less uptake in the brain. As a result, 2-[18F]-FDM (6) could be developed for selective imaging of brain tumours in the future.

2-[18F]-FDM (6) has also been investigated for the identification of plaque inflammation to image atherosclerosis. 96,97 Macrophages involved in this process consume higher levels of D-glucose compared to surrounding tissue within the plaque making this a prime candidate for p-glucose related PET imaging. In vivo rabbit studies found uptake of 2-[18F]-FDG (1) and 2-[18F]-FDM (6) via p-glucose transporters in atherosclerotic lesions was comparably high. Furthermore, in vitro studies in macrophages showed  $\sim 35\%$  higher uptake of 2-[18F]-FDM (6) over 2-[18F]-FDG (1) resulting from reduced hexokinase II inhibition. Antibody binding studies to D-mannose receptors expressed by M2 macrophages showed decreased antibody binding with  $2-[^{18}F]$ -FDM (6) but not with  $2-[^{18}F]$ -FDG (1). This preferred binding of 2-[18F]-FDM (6) could be harnessed in the future to detect progressive inflammation.

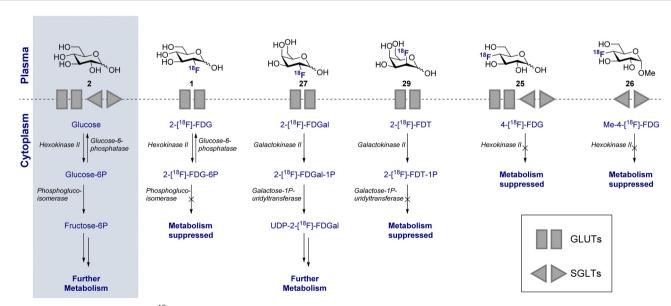
Another comparative study of 2-[18F]-FDG (1) and 2-[18F]-FDM (6) investigated specific labelling of the more commonly associated T lymphocyte-activating antigen (CD80) with two pyrazolocinnoline-based radiotracers in a mouse model. High accumulation of 2-[18F]-FDG (1) and 2-[18F]-FDM (6) in monocytes and macrophages that are present in atherosclerotic plague was observed through active transport using GLUTs. CD80 was found to be essentially involved in the inflammatory processes of atherosclerosis and therefore, could be useful as a marker in early diagnosis.97

### 3.5 p-Galactose-based <sup>18</sup>F radiotracers (Fig. 4E)

2-Deoxy-2-[18F]-fluoro-p-galactose (27) (2-[18F]-FDGal), the C4epimer of 2-[18F]-FDG (1) (Fig. 4E), was rigorously investigated

in the late 1980s to elucidate p-galactose metabolism pathways. 98 The parent monosaccharide, D-galactose, is a core building block in glycoprotein synthesis via phosphorylation, at the C1 position, to p-galactose-1-phosphate (Gal-1-P), and also serves as a central energy source through subsequent conversion of Gal-1-P to p-glucose via galactose-1-phosphate uridyltransferase and UDP galactose-4'-epimerase (Scheme 5).99 Although the galactokinases responsible for phosphorylation are prevalent throughout the body, they are most prolific in the liver. This reflects the importance of efficient D-galactose excretion in human health and its diagnostic importance. Initial biodistribution studies of 2-[18F]-FDGal (27) in rats highlighted a high liver to blood ratio, and this was confirmed in a second study in rabbits. An important finding of this study was the observation that subsequent administration of p-galactose decreased the levels of tracer in the liver. However, this effect was not observed after D-glucose (2) administration, indicating that uptake occurs through a competitive process with D-galactose (16) but not D-glucose (2). The authors also observed a correlation between 2-[18F]-FDGal (27) uptake and organospecific galactokinase activity, which followed the trend: liver > kidney > brain > muscle. This further supports the notion that uptake occurs through the D-galactose mechanism. Having established the mode of uptake, two main metabolites of 2-[18F]-FDGal (27) were identified. The phosphorylation product, 2-deoxy-2-[18F]-fluoro-D-galactose-1-phosphate, was formed immediately by galactokinase and was responsible for 81% of <sup>18</sup>F tracer activity. In addition, <sup>18</sup>F-FDGal-1-P, was further uridylated to UDP-[18F]-FDGal by UDP-glucose. It is noteworthy that these metabolites were also identified in the heart, lung, spleen and small intestine. 100

The D-galactose selectivity observed for liver tissue presented an array of opportunities for clinical translation and in 1989 a study reporting the application of 2-[18F]-FDGal (27) as a radiotracer for liver tumour imaging was reported. 101 Interestingly,



Scheme 5 Metabolism of various <sup>18</sup>F radiotracers in comparison to D-glucose (2).

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both metabolites (*vide supra*) were identified in liver tumours in mice (mammary carcinoma) and rats (Yoshida carcinoma). The efficiency of 2-[<sup>18</sup>F]-FDGal (27) in well differentiated hepatomas in mice and rats was also investigated leading to the conclusion that higher uptake in well-differentiated hepatomas (spontaneous hepatoma C3H mice) occurs than in hepatomas that were less differentiated (*e.g.* MH129P). From the perspective of tumour imaging, it is pertinent to highlight that 2-[<sup>18</sup>F]-FDGal (27) has been reported to outperform 2-[<sup>18</sup>F]-FDG (1), with tumour to tissue ratios of 13.7 and 6.46, respectively, having been noted in poorly differentiated hepatoma. <sup>94,99</sup>

In 2008, a report by Sørensen et al. quantified p-galactose (16) uptake and liver metabolism using 2-[18F]-FDGal (27). Ten pigs were anesthetised, injected with 2-[18F]-FDGal (27) and monitored by PET. The hepatic clearance rate of 2-[18F]-FDGal (27) was found to be 600 μmol min<sup>-1</sup> L<sup>-1</sup> in tissue, which is inline with previous studies, underscoring the potential of 2-[18F]-FDGal (27) as an accurate, non-invasive indicator of general liver health. 102 In 2011, the same group reported a study of 2-[18F]-FDGal (27) in 39 patients having either known hepatomas or suspected liver cancer was conducted. 103 The patients were administered with 2-[18F]-FDGal (27) intravenously and tumours were detected in 22 out of 23 patients with active liver cancer. Identical detection rates were noted with multiphase contrast-enhanced CT (ceCT). 2-[18F]-FDGal (27) has also been employed to determine dose-response relationships for Stereotactic Body Radiation Therapy (SBRT) to study liver metabolism (as well as recovery) in more detail. 104 Furthermore 2-[18F]-FDGal (27) has been successfully leveraged to measure liver function in vivo as an non-invasive alternative to arterial blood sampling.105

A structural isomer of 2-[18F]-FDGal (27), 6-deoxy-6-[18F]fluoro-p-galactose (28) (6-[18F]-FDGal) was also investigated for imaging p-galactose (16) metabolism. Moving the 18F-radiolabel to the C6-position instead of the C2-position, retained rapid biodistribution from the blood to the remaining tissues and organs. However, rapid excretion also ensued with 56% of the radiotracer found in the urine at 60 min p.i.

The C6–OH in p-galactose has previously been shown as a requirement for galactokinase binding. This was evident in the metabolites that were detected as only very low levels of 6-[<sup>18</sup>F]-FDGal-1P were detected in the liver in comparison to the nongalactokinase dependant oxidised metabolite galactonate, potentially aiding in rapid excretion. Furthermore, this tracer showed no competitive uptake with p-galactose. This, combined with the previous experiments determined the C6-OH is preferably left unsubstituted and as such the tracer was not further investigated.

# 3.6 D-Talose-based <sup>18</sup>F radiotracers (Fig. 4F)

2-Deoxy-2-[<sup>18</sup>F]-fluoro-D-talose (29) (2-[<sup>18</sup>F]-FDT) was synthesised by Diksic and Jolly in 1985 by an aqueous fluorination protocol. <sup>107</sup> Since this species is formally a C2 and C4 epimer of D-galactose and D-mannose, respectively, it is an attractive small molecule for the study of galactokinase activity (Fig. 4F and Scheme 5). Indeed, an earlier study by Alvarado demonstrated

that p-talose was phosphorylated by galactokinases in *Saccharomyces fragilis*. <sup>108</sup>

Biodistribution studies performed from the early 90s in tumour bearing mice (fibrosarcoma) revealed that the highest uptake occurred in the liver (34.9% dose per g), followed by kidney (15.9% dose per g) and small intestine (12.9% dose per g). However, 2-[18F]-FDT (29) was also characterised by high liver uptake in normal rats. This was inhibited by parallel administration of D-galactose, supporting the notion that a p-galactose uptake mechanism is operational, much like 2-[18F]-FDGal (27). These promising results were further expanded upon two years later by the same group. 110 Further NMR spectroscopic analysis determined that 2-[18F]-FDT-1phosphate was the only metabolite generated in tumourbearing mice (administration 60 mg  $kg^{-1}$ ). Furthermore, in vitro analysis revealed that 2-[18F]-FDT (29) is rapidly phosphorylated to 2-[18F]-FDT-1-phosphate by galactokinase, but subsequent uridylation does not occur. This indicates that the subtle C2 epimerisation (p-galactose versus p-talose), renders 2-[18F]-FDT (29) an unsuitable substrate for galactose-1-phosphate-uridyltransferase (Scheme 5). 2-[18F]-FDT-1-phosphate is thereby trapped in tumour tissue, ensuring accumulation for PET. Despite its appeal as a tracer for p-galactose metabolism, particularly as the lack of further metabolism simplifies data analysis, 2-[18F]-FDT (29) has been comparatively under-explored since the 1990s.

# 3.7 L-Fucose-based <sup>18</sup>F radiotracers (Fig. 4G)

In stark contrast to the epimeric PET tracers described Fig. 4C–F, L-fucose is a deoxysugar and that differs structurally on account of the deletion at C6 position and its inverted absolute configuration (L- versus D-). In mammalian systems, L-fucose is a ubiquitous component of N-linked glycans where it is frequently linked to the reducing end  $\beta$ -N-acetylglucosamine in glycolipids. Given the prevalence of glycolipids in the plasma membrane, they are important tumour biomarkers for cell growth, division, antigenicity and differentiation. Consequently, L-fucose-based PET analogues hold great promise in cancer diagnostic and personalised medicine.

In 1990, Ishiwata et al. examined 6-[18F]-fluoro-L-fucose (30) (6-[18F]-FFuc) as an avenue for monitoring glycoconjugate synthesis in tumours (Fig. 4G). 112 In vivo studies in FM3Abearing mice revealed that the main metabolite was GDP-6-[18F]-FFuc, thereby implicating guanidylation by GDP-fucosepyro-phosphorylase is being rate determining in metabolism. Upon co-administration of L-fucose, uptake of 6-[18F]-FFuc (30) was significantly impeded thereby indicating competition for the L-fucose uptake mechanism. Two years later, in a broader study of several sugar-based tracers across five different tumour models, 6-[18F]-FFuc (30) was found to have a much poorer uptake by tumour-bearing rats and mice than 2-[18F]-FDG (1). 113 Although uptake was comparatively low, the tumour to tissue ratio in the brain was far superior at 7.27  $\pm$  0.77 compared with  $1.28 \pm 0.45$  for 2-[18F]-FDG (1). Moreover, 2-[18F]-FdFuc (31) was also found to have a slightly improved uptake than its

counterpart 6-[18F]-FFuc (30), however showed lower tumour to tissue ratio in the brain at 2.88  $\pm$  0.48.

### Sialic acid-based <sup>18</sup>F radiotracers (Fig. 4H)

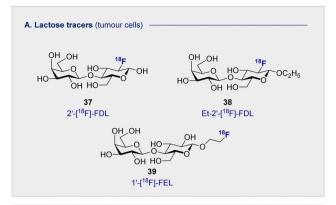
Sialic acids are mostly found at the termini of sugar chains and as such play an exceptional role in nature. Coating the cell surface, they control a wide range of biochemical processed e.g. cell recognition. Inspired by the prevalence of sialic acids in regulatory gangliosides on the plasma membrane, Ishiwata et al. prepared two 18F-N-acetyl-neuramic acid tracers, Nacetyl-3-[18F]-fluorosialic acid (32 and 33) (3-[18F]Neu5Ac-C3<sub>ax.</sub> and C3<sub>eq.</sub>) and N-acetyl-2-deoxy-2,3-difluorosialic acid (34) (2,3di[18F]Neu5Ac), to investigate glycoconjugate metabolism of tumours. 114 However, selective uptake could not be established across the range of tumour models that were tested in addition to poor overall uptake and high clearance rates. Even though sialic acids have shown little promise in PET, alternative methods e.g. Bertozzi's modified Staudinger reaction, for in vivo imaging of sialic acid surfaces have been developed. 115 Sialic acids are not only important for tumour progression, but also decorate the end of glycolipids e.g. gangliosides, and serve important regulatory purposes. For more information on gangliosides, please see Section 6, <sup>18</sup>F-Modified Ganglioside Tracers.

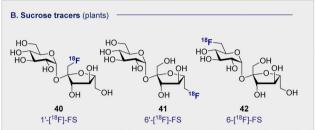
# 4. <sup>18</sup>F-modified disaccharide tracers

# 4.1 Lactose-based <sup>18</sup>F radiotracers (Fig. 8A)

The natural abundance of simple disaccharides, coupled with the modular nature of carbohydrates in a broader sense, manifests itself in the next level of PET tracer structural complexity. Lactose results from the union of p-glucose (2) and p-galactose (16) through a characteristic  $\beta$ -(1  $\pm$  4) glycosidic bond. Given the independent success of the constituent monosaccharides in nuclear medicine, 2'-[18F]-FDL (37) has been synthesised from 2-[18F]-FDG (1) via enzymatic catalysis leveraging galactosyl transferase.116 Specifically designed to visualise expression of the LacZ gene, the tracer unfortunately did not accumulate in any of the organs in normal mice and was rapidly excreted through the bladder.

The hepatocarcinoma-intestine-pancreas/pancreatitisassociated protein (HIP/PAP) is overexpressed in peritumoral pancreas and has previously shown to have a high affinity for Dlactose. Consequently, ethyl-2'-deoxy-2'-[18F]-fluorolactose (38) (Et-2'-[18F]-FDL) was later developed to facilitate imaging of pancreatic carcinoma and was found to bind specifically to peritumoral pancreatic tissue in mice (Fig. 8A). 117 A notable advance stemmed from the introduction of 1'-[18F]-FEL (39), a tracer with potentially similar activity to Et-2'-[18F]-FDL (38) but which could be accessed much more efficiently. 118,119 In tumour-bearing mice, 1'-[18F]-FEL (39) showed a significant increase of uptake in the peritumoral tissue (1.29  $\pm$  0.295% ID per g), in comparison with the wild type (0.090  $\pm$  0.010% ID per g). It is pertinent to note that uptake was determined by autoradiography rather than by the PET image due to poor resolution. 120 The uptake in the surrounding tissues, no





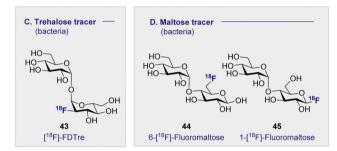


Fig. 8 Structures of disaccharide-based <sup>18</sup>F radiotracers.

significant difference was noted compared to the control mice: this is consistent with the previous discussion on the lactosebased tracer Et-2'-[<sup>18</sup>F]-FDL (38). Interestingly, 1'-[<sup>18</sup>F]-FEL (39) was shown to be selective for the peritumoral tissue and no tracer accumulation in the pancreas was observed in the control group mice.

### 4.2 Sucrose-based <sup>18</sup>F radiotracers (Fig. 8B)

Whilst <sup>18</sup>F-modified carbohydrates have a venerable history in studying mammals and bacteria, 18F PET is also a highly effective paradigm for the study of plant metabolism. Capitalising on the formation of sucrose as the ultimate product of photosynthesis, <sup>18</sup>F-labelled derivatives have been instrumental in this endeavour. In 2012, the Fowler group prepared 1'-[18F]fluoro-1'-deoxysucrose (40) (1'-[18F]-FS) through a concise sequence involving enzymatic synthesis of the triflate precursor with concomitant radiofluorination with K18F.121

This was followed by chemical syntheses of 6'-deoxy-6'[18F]fluorosucrose (41) (6'-[18F]-FS) and 6-deoxy-6[18F]-fluorosucrose (42) (6-[18F]-FS). 122 All three derivatives were successfully translocated confirming that OH to 18F bioisosterism does not Tutorial Review Chem Soc Rev

compromise membrane transport and underscores the utility of PET in the study of plant physiology and biochemistry. <sup>123</sup>

# 4.3 Trehalose-based <sup>18</sup>F radiotracers (Fig. 8C)

The persistent threat presented by antibiotic resistance has led The World Health Organisation to classify it as one of the top threats to human health. If current projections persist, bacterial resistance will surpass cancer as the leading cause of human deaths worldwide by 2050. This critical situation continues to be exacerbated by the unnecessary administration of antibiotics, often in scenarios in which a bacterial infection has not been confirmed. The development of selective diagnostic procedures to facilitate rapid, early detection is set to play a central role in alleviating this current crisis. Since clinical success is conditional on the ability to target pathogenic bacterial cells in the presence of eukaryotic cells, simple 18 F-modified oligomers have been intensively investigated to mitigate the lack of selectivity associated with 2-[18 F]-FDG.

Trehalose, a disaccharide comprised of two D-glucose subunits linked by a  $\alpha$ - $(1 \rightarrow 1)$  glycosidic bond, is readily uptaken by *Mycobacterium tuberculosis*; a process that has been studied by a FITC-labelled probe, <sup>125</sup> and leveraged for PET through the introduction of an <sup>18</sup>F-lablelled species. <sup>126</sup> This latter study revealed selective uptake of <sup>19</sup>FDTre analogues by SugABC-LpqY, which is a trehalose transporter in *Mycobacterium smegmatis* cells. Subsequent comparative studies in mammalian and bacterial cell have further cemented trehalose as a promising future tracer core, in particular [<sup>18</sup>F]-FDTre (43) tracer uptake shown at a picomolar level. <sup>127</sup> The suppression of uptake in *Mycobacterium smegmatis* when <sup>19</sup>F-trehalose is introduced further supports a trehalose-based uptake mechanism.

#### 4.4 Maltose-based <sup>18</sup>F radiotracers (Fig. 8D)

Targeted diagnosis of bacterial infection can be further expanded to include the maltose-based tracers. In particular, the exclusivity of the maltodextrin transport complex present in bacteria renders maltose, 128-130 and its higher oligomers, an attractive candidate for selective tracer development. 131,132 In 2014, Gambhir and co-workers reported the synthesis of 6-[18F]maltose (44) as an imaging probe and evaluated it in vitro. 133 When co-administered with maltose, uptake was supressed in Escherichia coli, suggesting the involvement of a common uptake pathway. Furthermore, the authors noted that whilst 6-[18F]-maltose (44) is sequestered by various bacteria, both Gram-positive and Gram-negative (Escherichia coli ATCC 33456, Pseudomonas. aeruginosa and Listeria monocytogenes), uptake by mammalian cancer cells (human breast cancer, human cervical cancer) was not observed. A murine model revealed that 6-[18F]maltose (44) accumulated in muscles that were infected with bacterial myositis but not in inflamed tissue: this is noteworthy given the clinical relevance of distinguishing between infection and inflammation. 134,135 However, the significant uptake observed in the blood and the slow clearance from major organs, i.e. brain, liver and kidneys, compromised image resolution. The same group have trialled 1-[18F]-fluoromaltose (44), but in vivo instability observed in the uptake experiments

resulted in defluorination and subsequent incorporation of the fluoride ion into the bone. 136

# 5. <sup>18</sup>F-modified oligosaccharide tracers

Of the naturally occurring oligosaccharides that have been considered for diagnostic applications using PET, maltodextrins have emerged as being particularly well-suited to the study of bacterial infections. Like their lower D-maltose (46) analogues, these polysaccharides are comprised of p-glucose (2) monosaccharides which are connected by  $\alpha$ - $(1 \rightarrow 4)$  glycosidic linkages. Their highly hydrophilic nature renders them impermeable to the cell membrane, thereby requiring the involvement of maltodextrin transporter proteins to facilitate cellular uptake. 137 In the case of 18F-radio-labelled derivatives, this physicochemical signature ensures that the target to background ratio is enhanced as residual tracer that is not taken into the bacterial cells is cleared rapidly and efficiently. The striking breadth of clinical specificity that can be realised by increasing molecular weight across the D-glucose (2), D-maltose (46), maltodextrin series serves to highlight unlocking the potential of seemingly simple sugars for their use in personalised medicine.

A report by Murthy and co-workers in 2011 described the application of a maltodextrin-based fluorescent imaging probe to detect bacteria *in vivo* with high sensitivity and specificity. <sup>138</sup> In this study, the authors report that maltodextrin transporters tolerate anomeric substitutions, suggesting that the reported label can be installed at the reducing end of the oligomer. As a proof of concept upon which to advance a PET tracer, two target compounds based on maltohexaose (47) were prepared with a fluorescent dye introduced by click chemistry.

Following incubation with Gram-positive and Gram-negative bacteria, accumulation in the millimolar range was noted in both cases. The initial findings were further corroborated by in vivo experiments in rats infected with E. coli. These findings based on the fluorescent probes provided a foundation for the subsequent advancement of a maltohexaose 18F-radio tracer for PET imaging (Fig. 9). 139 Substituting the terminal fluorescent dye with an <sup>18</sup>F motif, again via click chemistry, was performed. The authors observed high accumulation in bacterial cells during in vivo studies with Escherichia coli in rats, with [18F]maltohexaose (48) being selectively metabolised by bacteria, relative to 2-[18F]-FDG (1). Building on this success, a secondgeneration PET tracer, 6"-[18F]-fluoromaltotriose (49), was introduced in 2017 which is based on the shorter oligomer maltotriose. 140 The introduction of 6"-[18F]-fluoromaltotriose (49) led to improvements in both the pharmacokinetics and target-to-background ratios relative to 6-[18F]-maltose (44). It is interesting to note that 6"-[18F]-maltotriose (49) was less strongly absorbed into the blood and muscles, and that it showed a longer residence time in Escherichia coli, likely due to a slower metabolism of digesting maltotriose into D-glucose units. There are, however, several limitations that are worthy of

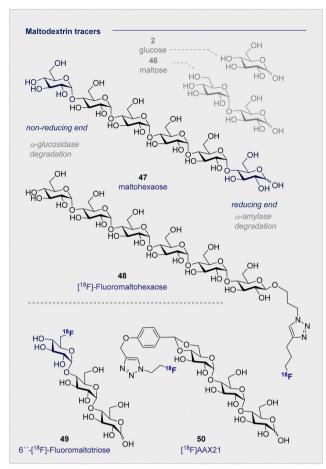


Fig. 9 Selected maltodextrin-based <sup>18</sup>F-radiotracers.

consideration. Maltodextrin-based PET tracers are only suitable to detect bacteria that are located extracellular, whereas intercellular scenarios such as Mycobacterium tuberculosis present a challenge.

Furthermore, the maltodextrin transport system is complex and can differ depending on the bacterial species (Gramnegative/positive). 141 Finally, enhancing serum stability is a core objective to mitigate tracer degradation in the blood: efficient hydrolysis by α-glucosidase (non-reducing end) and α-amylase (reducing end) is a persistent threat when utilising maltohexaoses that must be alleviated. To address these issues, Faust, Gilmour and co-workers initiated a study of maltosebased <sup>18</sup>F radiotracers of varying chain length (1-6 p-glucose units) to study their stability towards  $\alpha$ -amylase in blood. <sup>10,142</sup> An initial control experiment with a model maltodextrin substituted at the anomeric position confirmed degradation by α-glucosidase (at the non-reducing end) in blood. Following independent incubation of each <sup>18</sup>F-PET tracer in human blood serum, [18F]-maltopentaose and [18F]-maltohexaose were also found to undergo rapid degradation, whereas [18F]-maltotriose (50) ([18F]AAX21) showed promising stability (over 120 min, amylase activity 51 U L<sup>-1</sup>). Furthermore, incubation of the (50) [18F]AAX21 in murine serum, which has a 100-fold higher α-amylase activity, confirmed the stability of the tracer towards enzymatic hydrolysis. This indicates that the position of the label provides a structural handle by which to augment stability in vivo and, that for bacterial uptake, a free anomeric center is required on the terminal monosaccharide to access the cytoplasm through MalFGK<sub>2</sub>.  $^{128,130,143}$ 

# 6. <sup>18</sup>F-Modified ganglioside tracers

The monosialyl ganglioside GM1 is highly localised in the brain, specifically in the postsynaptic neuronal membranes, which renders it attractive in the study of neurodegenerative disorders. 144,145 In 2020, the Schou laboratory prepared an 18Fradiolabelled analogue of GM1, [18F]-GM1 (51) for study in the non-human primate brain (Fig. 10). 146 However, upon injection, a biodistribution study in a cynomolgus monkey essentially failed to identify a signal in the brain. The blood to brain ratio was found to be 0.03, indicating that the radioactivity recorded in the region could be attributed to the blood. This observation was further corroborated by an increased signal observed in the vessels peripheral to the blood brain barrier. The study also noted that high levels of [18F]-GM1 (51) accumulated in the heart. Given that elevated levels of GM1 have been linked to heart failure, this may compromise further development of the tracer. It is pertinent to note that monosialyl gangliosides GM3 and GM4 are also implicated in a plethora of neurodegenerative processes and constitute structurally simpler candidates for tracer development. A recent synthesis and pre-clinical-evaluation of a GM3-alkyne (52) has shown that the fluorinated epitope had no significant impact on oligodendrocyte viability, whereas the native epitope decreased viability in a dose dependent manner. 147 It is noteworthy that single site fluorination of the GM4 ganglioside epitope (F versus OH) led to an upregulation of oligodendrocyte

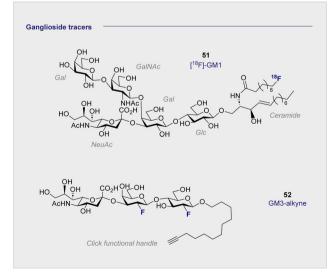


Fig. 10 Structures of modified gangliosides GM<sub>1</sub> (upper) and GM<sub>3</sub> (lower).

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differentiation: this underscores the modular nature of (fluorinated) carbohydrates and the opportunities that this presents in regulating biological function. 148

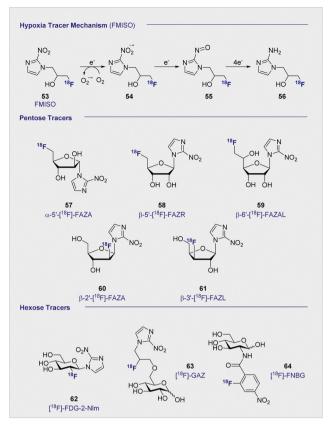
# <sup>18</sup>F-PET tracers to detect hypoxia

The principle uptake mechanisms associated with carbohydratebased PET tracer design (e.g. 2-[18F]-FDG (1)) traditionally centre on p-glucose metabolism pathways: these include active transport via GLUTs and/or SGLTs (see Section 3.3).

The clinical translation of candidates that leverage this strategy has proven to be highly successful, but the ubiquity of p-glucose metabolism in cellular metabolism frequently compromises specificity. This consideration becomes particularly acute when attempting to expand the repertoire of PET imaging agents to detect hypoxic tissue (deprivation of oxygen at the tissue level). In tumours, increased hypoxia often results from mutated structures being unable to fully oxygenate the affected cells. 149 Hypoxia has thus been associated with increased local tumour aggression, resistance to chemotherapy, 150,151 and probability of metastasis. 152,153 These hostile conditions promote the survival of malignant cells over healthy cells and inhibit the production of radical oxygen, which is an essential component of effective radiotherapy. 154 As such, the effective detection of hypoxia through PET-based imaging paradigms is essential in preliminary tumour prognosis. Varying the uptake method to enhance specificity for the target cells would therefore be highly advantageous for PET imaging in hypoxic environments.

# 7.1 <sup>18</sup>F FMISO – an alternative uptake mechanism

Uptake of the small-molecule PET tracer FMISO (53) occurs through passive diffusion (Scheme 6, upper). Once in the cell, the nitro group is sequentially reduced to the amine moiety thus providing a handle for bioconjugation (e.g. with e.g. glutathione): this ultimately facilitates intracellular bioaccumulation. 155 It is proposed that this mechanism is only effective in hypoxic conditions, since the presence of oxygen would lead the anionic radical intermediate to be converted back to the original FMISO (53) via superoxide radical formation. 156 Whilst details regarding the exact mechanistic pathway require clarification, the characteristics intrinsic to FMISO (53) render it ideally suited to the study of tumourassociated hypoxic tissue. In the clinic, FMISO (53) has been extensively studied as a hypoxia imaging probe across multiple tumour models, where it has shown to be particularly effective in head and neck tumours as well as breast cancer and gliomas. 157-159 However, the success and broad utility of FMISO-imaging is not without limitations, most notably poor tumour to background ratio. The paradigm is heavily disadvantaged by the relatively short biological half-life of 50 min, whereas PET tracing regions of hypoxia benefit from longer half-lives to improve image resolution. Longer halflives facilitate increased uptake by the hypoxic regions whilst allowing clearance from the background tissues. To combat this, the arabinose-derived PET tracer  $\alpha$ -5'-[18F]-FAZA (57), a



Scheme 6 (upper) Proposed, reductive mechanism, post-uptake, through passive diffusion. Oxygenated environment: the FMISO radical anion (54) is restored to its original structure through superoxide radical formation. Absence of oxygen: FMISO radical anion (54) is further reduced to amine (56) that can covalently bind macromolecules, resulting in accumulation of FMISO in the cell. (middle) Structures of selected, pentose-based hypoxia radiotracers (57-61). (lower) Structures of selected hexose-based hypoxia radiotracers (62-64).

carbohydrate derivative of FMISO (53), was developed. 160,161 In contrast to FMISO (53),  $\alpha$ -5'-[18F]-FAZA (57) is more hydrophilic thereby enabling the target to be reached faster, whilst being readily expelled through the urinary tract.

Although  $\alpha$ -5'- $[^{18}F]$ -FAZA (57) has not yet been approved by the FDA, it has shown great promise in animal and patient studies (Fig. 11). 162,163 One highly pertinent study investigated the effectiveness of  $\alpha$ -5'-[18F]-FAZA (57) on a cohort of 50 patients with solid tumours that included high-grade glioblastomas, small cell lung carcinoma and malignant lymphoma.<sup>164</sup> For patients with high-grade glioblastoma, the tumour to background ratio was as high as 15.6 with an average of 5.3  $\pm$  4.7 across 7 patients, partly attributed to poor uptake in normal brain tissue. This improvement in resolution relative to its predecessor subsequently prompted the development of a series of 2-nitroimidazole derivatives in attempt to further enhance cellular uptake. The beta derivative β-5'-[18F]-FAZR (58) was evaluated for utilising uptake pathways across the cell membrane to improve efficiency over its predecessor. 165 Binding experiments, to study uptake mechanism, with nucleoside

500 µm [18F]FDG

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pimonidazole antibody

Fig. 11 Comparison of  $2-[^{18}F]-FDG$  (1) A and  $[^{18}F]-FAZA$  (57) C on the same CT26 colon carcinoma. **B** The same CT26 colon carcinoma analyses ex vivo via H&E staining of tumor slices (region shown as red square in A and C). D and E Pimonidazole immunohistochemistry ex vivo. This research was originally published in Radiation Oncology: F. C. Maier, M. Kneilling, G. Reischl, F. Cay, D. Bukala, A. Schmid, M. S. Judenhofer, M. Röcken, H. J. Machulla and B. J. Pichler, Significant impact of different oxygen breathing conditions on noninvasive in vivo tumor-hypoxia imaging using [18F]-fluoro-azomycinarabino-furanoside ([18F]FAZA), Radiat. Oncol., 2011, 6, 165. Reused under the Creative Commons Attribution License (https://creativecommons.org/licenses/by/2.0)

transporters hENT1/2 and hCNT1/2/3 were carried out to study if  $\beta$ -5'-[<sup>18</sup>F]-FAZR (58) could act as an inhibitor of uridine uptake. Inhibition of all but hCNT3, showed IC<sub>50</sub> > 500  $\mu$ M. hCNT3 inhibition was shown to be comparable, though almost 2-fold weaker, to the thymidine control (IC50 = 65  $\pm$  4  $\mu M$  and 35 ± 5 μM respectively) indicating β-5'-[ $^{18}$ F]-FAZR (58) may utilise uptake via the hCNT3 transporter.

Another derivative of  $\alpha$ -5'-[<sup>18</sup>F]-FAZA (57),  $\beta$ -6'-[<sup>18</sup>F]-FAZAL (59), was specifically introduced by Wanek and co-workers to leverage SLC2A transporters. In particular, SLC29A1, was found to be effective in transporting  $\beta$ -6'-[18F]-FAZAL (59) both in and out of the cell, thereby improving tumour to background ratio. This is grounded in an amplified uptake of the tracer, which facilitates accumulation, and increased excretion which lowers the background signal. 166 A competition study under normoxic conditions revealed inhibition of 2-[18F]-FDG (1) uptake, which suggests an interaction with the D-glucose transporter systems: very little β-6'-[18F]-FAZAL (59) was retained in the tumours of Wistar rats (Walker 256 mammary carcinosarcoma) by comparison. As a result, no further studies under hypoxic conditions were conducted.  $\beta$ -2'-[<sup>18</sup>F]-FAZA (60), and  $\beta$ -3'-[<sup>18</sup>F]-FAZL (61) have also been prepared but, to the best of our knowledge, details regarding in vivo or in vitro testing have not been disclosed.167 In 2002, Patt and co-workers synthesised and evaluated a nitroimadazole FDG derivative, [18F]-FDG-2-NIm (62) to improve on [18F]-FMISO's slow kinetics. 168 In vivo studies in Wistar rats bearing Walker 256 rat mammary carcinoma found the majority of the tracer located in the kidneys as rapid as 2 min p.i and showed little accumulation in the tumour tissue so was not studied further. In 2012, Wuest et al. reported the synthesis of [18F]-GAZ (63) as a potential PET tracer leverage active transport over the passive diffusion observed with α-5'-[18F]-FAZA (57).169 Whilst in vivo studies in EMT-6 tumourbearing mice showed uptake in the tumour, the tracer did not accumulate over time resulting in a low, stagnating PET signal over the course of the 60 minute analysis. This was in sharp contrast to  $\alpha$ -5'- $\lceil^{18}F\rceil$ -FAZA (57), which is retained in hypoxic tissue and continues to accumulate over 60 min p.i. Although uptake was considered poor, the faster clearance rate from the surrounding tissues resulted in a similar SUV (0.66) to  $\alpha$ -5'-[18F]-FAZA (57) (0.74) 5 minutes p.i. Furthermore, competition studies with 2-[18F]-FDG (1) required 1 mM concentrations to observe an effect: this is two orders of magnitude higher than is required with D-glucose (2), suggesting that the uptake mechanism is distinct from that of 2-[18F]-FDG (1).

In 2011, the portfolio of tracers was further expanded to include glucosamine derivatives. 170 p-glucosamine has been shown to inhibit tumour growth both in vitro and in vivo, although the mechanism of inhibition is not fully understood. 171-173 [18F]-FNBG (64) was synthesised and compared in vivo in KM tumour-bearing mice with [18F]-FAG (24) (Scheme 6). Relative to  $[^{18}F]$ -FAG (24),  $[^{18}F]$ -FNBG (64) was found to have a lower tumour to muscle ratio of 5.68 and 4.00 respectively, and poorer accumulation in all organs was noted by comparison. However, the tracer displayed a marginally better tumour to blood ratio (3.79 and 4.40 respectively). Whilst 2-[18F]-FDG (1) is generally considered to out-perform glucosamine derivatives with regards to the scope of imaging efficiency, these findings may stimulate interest in delineating the mechanism by which p-glucosamine inhibits tumour growth: this in turn may provide guiding principles to enable the development of more targeted PET agents.

# 8. <sup>18</sup>F-modified nucleoside tracers

Nucleosides are the constituent building blocks of our genetic blueprint (DNA), and continue to be intensively studied in the context of molecular diagnostic development. They consist of a nucleobase (either a purine or pyrimidine) linked to a pentose subunit by a characteristic  $\beta$ -glycosidic bond. Consequently, this class of small molecules is appealing for the development of novel PET tracers, specifically to monitor tumour-cell proliferation.

#### 8.1 Pyrimidine tracers

Upon inspection of the current suite of <sup>18</sup>F-nucleoside tracers, it is immediately apparent that the most widely studied system to date is thymidine. This is largely due to it being DNA specific, whilst its de-methylated counterpart uracil is found as its replacement in RNA. In a therapeutic regime, cellular uptake of thymidine tracers is followed by efficient phosphorylation by kinases, such that the now negatively charged species cannot leave the cell. This important feature ensures tracer accumulation and prevents rapid clearance from tumour cells, but does not impact clearance from the blood. It logically follows that the site of <sup>18</sup>F radiolabelling has been extensively studied on

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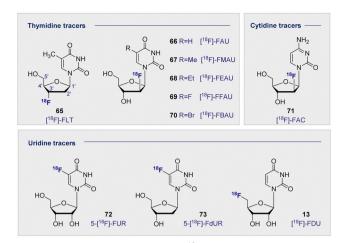


Fig. 12 Structures of selected <sup>18</sup>F-modified pyrimidine-based radiotracers.

both the sugar and the nucleobase moieties. From the structure-activity data available, <sup>18</sup>F substitution at the C2′ and C3′ position of the sugar ring is most effective. These regioisomers are characterised by an enhanced stability towards cleavage of the *N*-glycosidic bond by phosphorylases. In the case of the C2 systems, fluorine stereoelectronic effects manifest themselves in a characteristic puckering of the furanose ring. <sup>174–176</sup> As such the most studied analogues to date have become [<sup>18</sup>F]-FLT (65) and [<sup>18</sup>F]-FMAU (67) (Fig. 12).

[18F]-FLT (65) was first developed to address the time constraints imposed with using its predecessor, 11C-labelled thymidine, due to its relatively short half-life of 20 min. By comparison, the 18F analogue extended the effective life of the compound significantly. This compound undergoes sequential phosphorylations by cytosolic thymidine kinases (TK1 and TK2) to give the triphosphate of FLT. Substitution (C3'OH-<sup>18</sup>F) prevents any further DNA ligation, thus the molecule cannot be further metabolised or incorporated into the DNA, and instead accumulates in proliferating cells. Since increased cell proliferation has been correlated with increased cytosolic thymidine kinase activity, [18F]-FLT (65) and other structurally related nucleoside derivatives are promising PET imaging agents. 177 Furthermore, a close correlation has been observed between antigen Ki-67 (a known nuclear protein associated with cell proliferation) and [18F]-FLT (65) uptake in many tumour cell lines, suggesting that an increased accumulation of [18F]-FLT (65) could be associated with increased cell proliferation. 178-180

A clinical trial of 47 patients exhibiting malignant pulmonary nodules was carried out in 2005. [18 F]-FLT (65) uptake was exclusive to malignant tumours and enabled successful detection of malignancies in 32 patients. However, false negatives were observed in 6 patients with non-small cell lung carcinoma, pulmonary carcinoid and lung metastases. Further studies carried out between 2003 and 2016 have consistently reported that [18 F]-FLT (65) has a higher specificity but lower uptake when compared to 2-[18 F]-FDG (1). This suggests that whilst less [18 F]-FLT (65) actually makes it into the cell, the

likelihood of the tumour being malignant is higher if uptake occurs. [18F]-FLT (65) therefore has an important role to play in the early diagnosis of malignant lesions, particularly if further structural modifications lead to improved cellular uptake.

Related pyrimidine nucleosides in which the 3'-OH is free for DNA ligation and subsequent incorporation have also been investigated. Early studies of [18F]-FAU (66) in dogs showed even retention in all organs except for the expected accumulation in the excretion pathway. 183 Whilst significant accumulation in the bone marrow was expected, due to high concentrations of proliferating tissues, this is where the lowest retention of all was noted. Consequently, further development of [18F]-FAU (66) lost momentum and second-generation analogues were introduced (R group substitution, Fig. 12). [18F]-FMAU (67),  $[^{18}F]$ -FEAU (68),  $[^{18}F]$ -FFAU (69) and  $[^{18}F]$ -FBAU (70) have been investigated as potential imaging agents for suicide gene expression, in particular herpes simplex virus type 1 thymidine kinase (HSV1-tk) expression. 183-187 HSV1-tk is a gene that, when expressed, can be the focus of chemotherapy strategies. Suicide genes encode enzymes that can convert pro-drugs into active drugs as part of a therapeutic regime. HSV1-tk, when coupled with ganciclovir, has been successfully used to treat prostate cancer.

Across these studies, tumour uptake was found to be highest when [ $^{18}$ F]-FFAU (69) was administered and lowest with [ $^{18}$ F]-FEAU (68) giving rise to the following trend: [ $^{18}$ F]-FFAU (69) > [ $^{18}$ F]-FMAU (67) > [ $^{18}$ F]-FBAU (70) > [ $^{18}$ F]-FEAU (68). Even though [ $^{18}$ F]-FEAU (68) led to the lowest uptake, it was found to be preferentially phosphorylated by HSV1-tk and thus visible in colon cancer cells over the wild-type healthy cells. [ $^{18}$ F]-FMAU (67) is currently in phase I clinical trials, however, poor permeability across the blood–brain-barrier remains a limitation that excludes its use in monitoring cell proliferation in the brain.

A plenum of pyrimidine analogues based on uracil (14) and cytosine have also been investigated. 5-fluorouracil (5-FU) is a known cytostatic agent; however, its toxicity precludes clinical application. It was thought that uridine derivatives might circumvent this toxicity by acting as a pro-drug, being converted into 5-FU once it reached its target. Furthermore, uridine-based analogues confer a range of advantages due to their specificity for RNA over DNA. Like their thymidine DNA counterparts, <sup>18</sup>F substitution has been investigated on both the sugar and the nucleobase regions. 5-[<sup>18</sup>F]-FUR (72) and its deoxy derivative 5-[<sup>18</sup>F]-FdUR (73) were examined in the 1980s, and a study carried out in AH109A-bearing rats, disclosed that both showed good tumour to blood ratios (3.49 and 6.12 respectively) after 60 min. These high ratios were aided by rapid clearance from the blood and moderate tumour to tissue ratios. <sup>188</sup>

More recently, PET tracers derived from cytosine have become a subject of increasing interest, in particular 1-(2'-deoxy-2'-[<sup>18</sup>F]-fluoroarabinofuranosyl) ([<sup>18</sup>F]-FAC) (71). [<sup>18</sup>F]-FAC (71) was identified from a dCK activity *in vitro* screen of nucleosides to be retained in proliferating cells. <sup>189</sup> Biodistribution in mice showed accumulation in the thymus and the spleen, to a larger extent than was observed with 2-[<sup>18</sup>F]-FDG

(1). Anti-tumour response model studies showed high accumulation in the primary and secondary lymphoid organs, but very little signal in the tumour itself. It has also been determined that [18F]-FAC (71) accumulated in autoimmune models but not in viral hepatitis. 190 This contrasts with 2-[18F]-FDG (1), which did not enable discrimination and had similar accumulation in both. A further study investigated the potential of  $[^{18}F]$ -FAC (71) to visualise brain-infiltrating leukocytes in multiple sclerosis. 191 Unfortunately, comparable selectivity was not observed in this model as for the hepatitic immunity mouse. This is postulated to be due to brain infiltrating leukocytes dividing slower, which reduces the consumption of high levels of radiotracer. It is pertinent to note that when the chlorinated analogue, 2-chloro-2'-deoxy-2'-[<sup>18</sup>F]-fluoro-9-β-D-arabinofuranosyl-adenine (76) [<sup>18</sup>F]-CFA), was tested in humans, it did not cross the blood-brain barrier.191

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# 9. <sup>18</sup>F-modified purine tracers

In analogy to the pyrimidine tracers, substitution at the C3' on the furanose core was envisaged to promote cellular accumulation by blocking further metabolism through phosphorylation. Fluorinated adenosine analogues have previously been evaluated for anti-viral and anti-tumour activity: C2' fluorine substituted analogues showed potential in chemotherapeutic development, whereas C3' substitution facilitated antiviral activity. 192-194 A comparative study of the two adenosine tracers  $[^{18}F]$ -FXA (74) and  $[^{18}F]$ -FAA (75) (Fig. 13, top left), differing only by the site of <sup>18</sup>F substitution at either the C3' or C2' of the sugar, in tumour-bearing mice (human colon cancer xenografts) showed rapid clearance from the blood within the first 20 min. 195

Accumulation in the heart was postulated to be a result of interaction with adenosine receptors found within the organ, such that the tracer was interacting similar to the native adenosine. Micro-PET studies determined that [18F]-FAA (75) accumulated in the tumour tissue, whereas [18F]-FXA (74) accumulated predominantly in the heart with no significant signal in the tumour. This strikingly different behaviour is grounded in a single site shift of the <sup>18</sup>F substituent and further underscores the importance of the structure-function interplay in tracer development.

2-Chloro-2'-deoxy-2'-[18F]fluoro-9-β-D-arabinofuranosyladenine (76) ([18F]-CFA) has also been recently explored as a tracer for deoxycytidine kinase (dCK) activity. 196 [18F]-CFA (76) showed accumulation in leukemia cells in correlation with dCK expression. This response was also observed in human studies where accumulation was observed in tissues showing high dCK expression i.e. secondary lymphoid organs and the hematopoietic bone marrow. This was later extended to image dCKdependent proliferation in hepatocellular carcinoma (HCC). 197 Initial biodistribution studies highlighted most uptake in the bladder, liver, kidney and spleen. 198 As a result, imaging HCC required modifications to combat background signal from healthy liver tissue. This was later achieved through the

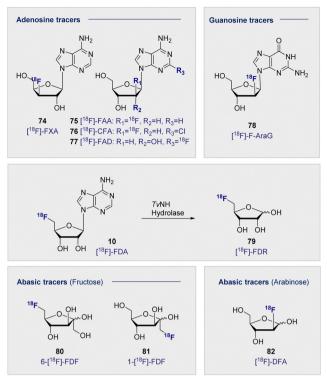


Fig. 13 Structure of selected adenosine and quanosine tracers (top). Hydrolysis of 5'-[18F]-FDA (10) to [18F]-FDR (79) (middle). Structure of selected abasic ribose tracers (bottom).

co-administration of cold <sup>19</sup>F-CFA. <sup>197</sup> It is interesting to note the structural similarities of the sugar core between [18F]-CFA (76) and the cytosine derivative [18F]-FAC (71), given the successful targeting of the same pathway. Substitution on the adenine base has also been explored as a PET tracer for imaging malignancies. 2-[18F]-Fluoroadenosine (77) (2-[18F]-FAD) was synthesised through a 2-nitroadenosine precursor and injected into Sprague-Dawley rats to obtain biodistribution data. 199 High accumulation was noted in the lung, heart and kidneys 60 min p.i. Accumulation in the lung was more than 2-fold observed in the heart and kidneys suggesting there could be a specific uptake or receptor that could be exploited for further development in the lungs.

2'-Deoxy-2'-[<sup>18</sup>F]-fluoro-9-β-D-arabinofuranosylguanine (78) ([18F]-F-AraG) was advanced for imaging T-cell activation when cell studies confirmed uptake of the tracer in primary T cells from mouse tissue.200 This tracer has been effectively deployed to image immune cells in the CNS, where tracer uptake has been shown to be strongly associated with areas of high T-cell concentration in the brain.201 As described in Schemes 3, 5'-[18F]-FDA (10) can be efficiently prepared through enzymatic synthesis. 50 This technology has been utilised to prepare the abasic tracer 5-[18F]-Fluoro-5-deoxyribose (79) ([18F]-FDR) to image tumour-bearing mice (injection of A431 cells).202 Specifically, nucleoside hydrolase was harnessed to hydrolyse the base, thereby generating abasic  $[^{18}F]$ -FDR (79) for use in vivo (Fig. 13, centre). In a comparison with  $2-[^{18}F]-FDG$  (1),  $[^{18}F]-FDR$  **Tutorial Review** Chem Soc Rev

(79) had a reduced residence time in the tumour, most likely due to lack of trapping from phosphorylation observed with 2-[18F]-FDG (1). Importantly, [18F]-FDR (79) showed comparable tumour to background contrast (10 min p.i.), rendering this tracer of great interest for further study in tumour lines that cannot be effectively imaged using 2-[18F]-FDG (1).

In addition to [18F]-FDR (79), other abasic, pentose-based tracers have shown varying degrees of success. Fluorinated fructose analogues 6-deoxy-6-[18]fluoro-p-fructose (80) 6-[18F]-FDF and 1-[18F]Fluorodeoxyfructose (81) (1-[18F]-FDF) (Fig. 13, bottom) have been developed to study fructose uptake via GLUT2 and GLUT5. Fructose is phosphorylated once in the cell by two distinct mechanisms. This may occur at the C1 position by ketohexokinase (fructokinase) or at the C6 position by hexokinase II. These two processes are noteworthy and provide a degree of orthogonality: blocking the correct site by design enabled either pathway to be elucidated.

GLUT5 has been shown to be overexpressed in certain tumour types, including breast cancer. This is of particular interest as GLUT1 (p-glucose uptake) has been shown to be under-expressed in certain cancers, leading 2-[18F]-FDG (1) to be less effective. In this regard, fructose offers potential in tumour tracking as it constitutes an alternative energy pathway to glycolysis.

Radiolabelling fructose at the C1 position to generate 1-[18F]-FDF (81) has revealed that uptake can be observed in the kidneys and liver, however rapid clearance and a lack of retention was observed.<sup>203</sup> 6-[<sup>18</sup>F]-FDF (80) was subsequently synthesised to study imaging in breast cancer in 2009.<sup>204</sup> This study noted that administration of the tracer led to inhibition of fructose and p-glucose transport, suggesting interaction with GLUT2 and potentially GLUT5. 6-[18F]-FDF (80) has been studied in EMT-6 and MCF-7 tumour-bearing mice (breast cancer). The analysis concluded that uptake was not impeded by the coadministration of p-glucose but that it was significantly reduced with co-administration of fructose, suggesting an uptake pathway similar to the native fructose.205 Furthermore, when 6-[18F]-FDF (80) was incubated with fructokinase, the phosphorylated product was generated, confirming that it is a competent substrate for fructokinase. By contrast, no phosphorylation was observed when incubated with hexokinase II, which can be rationalised on a structural level with the <sup>18</sup>F label inhibiting enzyme activity. 6-[18F]-FDF (80) tumour uptake was observed in EMT-6 tumour-bearing BALB/c mice and was visible 2 h p.i. The experiment was repeated with 2-[18F]-FDG (1), which gave similar results although the signal increased over time: the opposite was noted with 6-[18F]-FDF (80). At the 2 h time point, accumulation in bone was visible, potentially suggesting defluorination of the tracer. In MCF-7 tumour-bearing mice, the tumour was less visible p.i. with 6-[18F]-FDF (80), but the signal did not decrease as rapidly over the 2 h. Although 2-[18F]-FDG (1) showed higher retention, 6-[18F]-FDF (80) displayed good tumour-selectivity which facilitated image analysis. As recently as 2022, 6-[18F]-FDF (80) was evaluated as an agent to image microglia as part of an effort to elucidate the relationship between neuroinflammation and

neurodegenerative disease. In a study in LPS injected rodents, increased accumulation was seen in ipsilateral striatum over contralateral (0.985  $\pm$  0.047 and 0.819  $\pm$  0.033 SUV respectively). This result highlighted the potential of 6-[18F]-FDF (79) to image the brain's microglial GLUT5 density for further investigation into neurodegenerative disease.206

Finally, [18F]-2-deoxy-2-fluoroarabinose (82) ([18F]-DFA), an arabinose analogue, was evaluated as a ribose salvage probe. 207 [18F]-DFA (82) was successfully deployed to determine the accumulation of ribose in the liver. When administered to mice with metabolic syndrome, a decrease in uptake of [18F]-DFA (82) was observed, potentially indicating a correlation between ribose accumulation and D-glucose and/or fat metabolism.

# 10. Conclusions

This Tutorial Review is intended to serve as a structure-function guide of glycan-based radiotracers for 18F-PET from a chemical perspective. It is envisaged that this reference source will lower the barrier to entry for non-specialists who wish to contribute to this rapidly expanding field of molecular imaging. To further assist in navigating the landscape of this exciting field, a summary appendix of this review is provided (Appendix I). Conventional approaches to radiotracer development are now being complemented by enabling methodologies that range from small molecule strategies through to biocatalysis paradigms: bridging the gap from the laboratory to the clinic remains a decisive factor in achieving success. Further innovation will likely stem from the global production and widespread availability of 2-[18F]-FDG (1), which renders it attractive as a carbohydrate building block for practitioners who do not have access to cyclotron facilities.208

# **Abbreviations**

[ <sup>18</sup> F]-CFA	2-Chloro-2'-deoxy-2'-[ <sup>18</sup> F]-fluoro-9-
	β- <sub>D-A</sub> rabinofuranosyl-adenine
[ <sup>18</sup> F]-DFA	[ <sup>18</sup> F]-2-Deoxy-2-fluoroarabinose
[ <sup>18</sup> F]-FDTre	2-Deoxy-2-[ <sup>18</sup> F]-fluoro-p-trehalose
[ <sup>18</sup> F]-FAA	2'-Deoxy-2'-[ <sup>18</sup> F]-fluoro-1-β- <sub>D</sub> -
	arabinofuranosyl-adenine
[ <sup>18</sup> F]-FAraG	2'-Deoxy-2'-[ <sup>18</sup> F]-fluoro-9-β- <sub>D</sub> -
	arabinofuranosylguanine
[ <sup>18</sup> F]-FAC	1-(2'-Deoxy-2'-[ <sup>18</sup> F]-
	fluoroarabinofuranosyl)
[ <sup>18</sup> F]-FAG	<i>N</i> -[ <sup>18</sup> F]Fluoroacetylglucosamine
[ <sup>18</sup> F]-FAU	1-(2'-Deoxy-2'-fluoro-β-D-
	arabinofuranosyl)uracil
[ <sup>18</sup> F]-FBAU	1-(2-Deoxy-2-[ <sup>18</sup> F]-fluoro-β- <sub>D</sub> -
	arabinofuranosyl)-5-bromouracil
[ <sup>18</sup> F]-FDG-2NIm	1-(2-Deoxy-2-[ <sup>18</sup> F]-fluoro-β- <sub>D</sub> -
	glucopyranosyl)-2-nitroimidazole
[ <sup>18</sup> F]-FDR	5-[ <sup>18</sup> F]-Fluoro-5-deoxyribose

[ <sup>18</sup> F]-FEAU	2-Deoxy-2-[ <sup>18</sup> F]-fluoro-1,3,5-tri-O-	DNA	Deoxyribonucleic acid
[ <sup>18</sup> F]-FFAU	benzoyl-α-D-ribofuranose 2'-Deoxy-2'-[ <sup>18</sup> F]-fluoro-5-fluoro-1-	EMT-6	Ephithelial mesenchymal transition- 6 (mouse mammary carcinoma cell
40	β-D-arabinofuranosyluracil		line)
[ <sup>18</sup> F]-FMAU	2'-Deoxy-2'-[ <sup>18</sup> F]-fluoro-5-methyl-1- β-D-arabinofuranosyluracil	Et-2'-[ <sup>18</sup> F]-FDL	Ethyl-2'-deoxy-2'-[ <sup>18</sup> F]- fluorolactose
[ <sup>18</sup> F]-FNBG	N-(2-[ <sup>18</sup> F]-Fluoro-4-	FITC	Fluorescein isothiocyanate
	nitrobenzoyl)glucosamine	FMISO	Fluoromisonidazole
[ <sup>18</sup> F]-FLT	3'-Deoxy-3'-[ <sup>18</sup> F]fluorothymidine	Gal-1-P	D-Galactose-1-phosphate
[ <sup>18</sup> F]-FXA	3'-Deoxy-3'-[ <sup>18</sup> F]-fluoro-1-β-D-	GDP	Guanosine diphosphate
	xylofuranosyl-adenine	Glucose-6P	Phosphorylated D-glucose
[ <sup>18</sup> F]-GAZ	N-(2-[ <sup>18</sup> F]Fluoro-3-(6- <i>O</i> -	GLUT	D-Glucose transporter
	glucosyl)propyl-azomycin	GM1	Monosialotetrahexosylganglioside 1
1-[ <sup>18</sup> F]-FDF	1-[ <sup>18</sup> F]Fluorodeoxyfructose	GM3	Monosialotetrahexosylganglioside 3
1'-[ <sup>18</sup> F]-FS	1'-Deoxy-1'-[ <sup>18</sup> F]-fluorosucrose	GMP	Good manufacturing practice
2-[ <sup>18</sup> F]-AFDG	1,3,4,6-Tetra-acetyl-2-[ <sup>18</sup> F]-2-deoxy-	HIP/PAP	Hepatocarcinoma-intestine-
. ,	fluoro-p-glucose		pancreas/pancreatitis-associated
2-[ <sup>18</sup> F]-DFDG	2-Deoxy-2,2-[ <sup>18</sup> F]-difluoro- <sub>D</sub> -		protein
	glucose	HK-II	Hexokinase II
2-[18F]-FDG or [18F]FDG	2-Deoxy-2-[ <sup>18</sup> F]-fluoro-p-glucose	HSV1-tk	Herpes simplex virus type 1 thymi-
2-[ <sup>18</sup> F]-FDGal	2-Deoxy-2-[18F]-fluoro-p-galactose		dine kinase
2-[ <sup>18</sup> F]-FDM	2-Deoxy-2-[18F]-fluoro-D-mannose	L-AAO	L-Amino acid oxidase
2-[ <sup>18</sup> F]-FDT	2-Deoxy-2-[18F]-fluoro-D-talose	lacZ gene	Lactose operon (functional unit of
3-[ <sup>18</sup> F]-FDG	3-Deoxy-[ <sup>18</sup> F]-fluoro-p-glucose		DNA responsible for transport and
5'-[ <sup>18</sup> F]-FDA	5'-Deoxy-5' [18F]-fluoroadenosine		metabolism of lactose in <i>E. coli</i> )
5-[ <sup>18</sup> F]-FdUR	[18F]-5-Fluorodeoxyuridine	M2	M2 macrophage subtype
5-FU	5-Fluorouracil	MR	D-Mannose receptor (macrophage)
5-[ <sup>18</sup> F]-FUR	[18F]-5-Fluorouridine	MCF-7	Michigan cancer foundation -7
6-[ <sup>18</sup> F]-FDF	6-Deoxy-6-[18]fluoro-p-fructose		(breast cancer cell line)
6-[ <sup>18</sup> F]-FDG	6-Deoxy-6-[18F]-fluoro-D-glucose	NMR	Nuclear magnetic resonance
6-[ <sup>18</sup> F]-FS	6-Deoxy-6[18F]-fluorosucrose	PET	Positron emission tomography
6'-[ <sup>18</sup> F]-FS	6'-Deoxy-6' [18F]-fluorosucrose	p.i.	Post injection
6-[ <sup>18</sup> F]-FFuc	6-[ <sup>18</sup> F]-Fluoro- <sub>L</sub> -fucose	PNP	Purine nucleoside phosphorylase
$\alpha$ -5' -[ <sup>18</sup> F]-FAZA	1-α-D-(5-Fluoro-[ <sup>18</sup> F]-5-	RCY	Radiochemical yield
	deoxyarabinofuranosyl)-2-	RNA	Ribonucleic acid
	nitroimidazole	SAM	S-Adenosyl-methyltransferase
αMe-4-[ <sup>18</sup> F]-FDG (Me-4FDG)	) α-Methyl-4-[ <sup>18</sup> F]-fluoro-4-deoxy- <sub>D</sub> -	SBRT	Stereotactic body radiation therapy
	glucopyranoside	SGLT	Sodium-dependent D-glucose cotran-
$\beta$ -2'-[ $^{18}$ F]-FAZA	1-β-D-(2-Deoxy-2-[ <sup>18</sup> F]-		sporters
	fluoroarabinofuranosyl)-2-	SUV	Standardised uptake value
	nitroimidazole	$t_{1/2}$	Half life
$\beta$ -3'-[ $^{18}$ F]-FAZL	1-β-D-(3-Deoxy-3-[ <sup>18</sup> F]-	TK1/TK2	Cytosolic thymine kinases
	fluorolyxofuranosyl)-2-	TP	Thymidine phosphorylase
	nitroimidazole	UDP	Uridine diphosphate
$\beta$ -5'-[ <sup>18</sup> F]-FAZR	1-β-d-(5-Deoxy-5- $[^{18}F]$ -		
	fluororibofuranosyl)-2-		
	nitroimidazole		
$\beta$ -6'-[ <sup>18</sup> F]-FAZAL	1-(6'-Deoxy-6'-[ <sup>18</sup> F]fluoro-β- <sub>D</sub> -	<b>Author contribut</b>	ions
	allofuranosyl)-2-nitroimidazole		
AH109A	Hepatoma cell line	The article was written thro	ough contributions from all authors.
СЗН	Mouse strain (high spontaneous		
	frequency of mammary tumours)		

# Conflicts of interest

There are no conflicts to declare.

Contrast-enhanced

Central nervous system

Deoxycytidine kinase

tomography

computer

ceCT

**CNS** 

dCK

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# Appendix I

							Re
Compound no.	ıd Name	Target	Labelling Method	Model	Measurement	Comments	veic. Ref.
1	$2-[^{18}\mathrm{F}]\mathrm{-FDG}$	p-Glucose metabolism	Nucleophilic	Rat (Sprague Dawley)	Tumour: muscle ratio (90 min) = 4.75	Tumour: muscle ratio (90 Gold standard PET tracer, widely effective but difficult min) = 4.75 to target specific targets due to ubiquity of p-glucose uptake.	89
20	$3-[^{18}\mathrm{F}]\mathrm{-FDG}$	D-Glucose metabolism: Brain and heart	Nucleophilic	Rat (Sprague Dawley)	Tumour: muscle ratio $(120 \text{ min}) = 3.12$	Lower uptake than 2-[ <sup>18</sup> F]-FDG in heart, liver and kidneys and slower clearance.	89
21	$2  ext{-} [^{^{18}} ext{F}]  ext{-}  ext{DFDG}$	p-Glucose metabolism: Hexokinase activity	Electrophilic	Mouse (UBC, CD-1)	Brain: blood (60 min) = 2.75 Heart: lung (120 min) = 9.43	$2^{-[^{18}F]}$ -DFDG showed similar ratios to $2^{-[^{18}F]}$ -FDG (Heart: Lung = 12.0) but background uptake in Rhesus monkey much higher for $2^{-[^{18}F]}$ -DFDG.	69
22	$2 \cdot [^{^{18}}\mathrm{F}]  ext{-AFDG}$	p-Glucose metabolism: GLUT vs diffusion and relationship to hexokinase	Nucleophilic	Human colon adeno- carcinoma cell LS180		Increased lipophilicity increased tracer uptake through 70 diffusion in comparison to $2-[^{18}F]$ -FDG. GLUT independent.	1 70
23	$6-[^{18}\mathrm{F}] ext{-FDG}$	D-Glucose transport	Nucleophilic	Rat (Sprague Dawley)	I	Increased radioactivity observed in skeletal muscle in presence of insulin.	73
24	[ <sup>18</sup> F]-FAG	Tumour detection	Nucleophilic	KM tumour bearing mice	Tumour: muscle ratio (60 min) = 5.68 Tumour: blood ratio (60 min) = 3.79	KM tumour bearing mice Tumour: muscle ratio (60 Study compared to [ <sup>1.8</sup> F]-FNBG min) = 5.68 Tumour: blood ratio (60 min) = 3.79	170
25	$4-[^{^{1}8}\mathrm{F}]\mathrm{-FDG}$	SGLT vs GLUT uptake studies	Nucleophilic	Mouse Wild type (wt)	Kidney uptake (60 min): 4% ID per g (wt) $\sim 20\%$ ID per g ( $Glut2$ -)	Uptake by both SGLT and GLUTs. Accumulates in the brain comparable to 2-[ <sup>18</sup> F]-FDG in wt. Accumulated in kidneys in Glut2 knockout.	06
26	$lpha$ -Me-4- $[^{18}\mathrm{F}]$ -FDG	Sodium p-glucose cotran- Nucleoph sporter (SGLT) activity (high grade astrocytomas)	- Nucleophilic	Glut2 knockout ( <i>Glut2-</i> ) Human	ut2-) ur) = 1.67 io = 11.5	SGLT specific uptake. Low background signal in normal 93 brain tissue allows better imaging.	1 93
9	$2-[^{18}\mathrm{F}]\mathrm{-FDM}$	Atherosclerotic plaques	Nucleophilic	ApoE KO-cuff HFD mice	SUV comparable with 2-[ <sup>18</sup> F]-FDG, and sevenfold larger than [ <sup>11</sup> C]AM7	$2-l^{18}F$ ]-FDM determined not to be superior to $2-l^{18}F$ ]-FDG in atherosclerotic imaging and binding to MMR was insignificant.	26
		Hepatocullular carcinoma	Nucleophilic	AH109A bearing Donryu rats	Tumour: muscle ratio = 5.30	Ratio comparable to 2-[ <sup>18</sup> F]-FDG (6.20). However lower uptake in the brain suggests potential as brain tumour imper.	95
27	2-[ <sup>18</sup> F]-FDGal	Нераtота	Electrophilic	Hepatoma-bearing C3H mice	Tumour: blood ratio (60 min) = 12.7 Tumour: muscle ratio (60 min) = 24.2	Efficient on well differentiated hepatomas but less effective on poorly differentiated hepatomas.	66
28	6-[ <sup>18</sup> F]-FDGal	D-Galactose metabolism	Nucleophilic	ddY mice	Tumour: muscle ratio (30 min) = 1.73	Tumour: muscle ratio (30 Mean of three average ratios: (range was $1.02-2.55$ ) min) = $1.73$	106
29	[ <sup>18</sup> F]-FDT	Galactokinase activity and cancer	Nucleophilic	Fibrosarcoma bearing mice	Tumour: muscle ratio (120 min) = 5.43	Co-administration of tracer with p-galactose inhibited liver uptake of [ <sup>18</sup> F]-FDT in rats. Substrate for Galactokinase but not Galacto-IP-uridyltransferase.	109
30	6-[ <sup>18</sup> F]-FFuc	Glycoconjugate synthesis Nucleoph in tumours	. Nucleophilic	Tumour bearing rats: (AH109A, YS, KEG1). Tumour bearing mice: (FM3A, 311.)	Tumour: brain ratio (120 min) = 9.17 Tumour: muscle ratio (120 min) = 4.60	Values of tumour: tissue are an average over five cell lines.	Chem 5
31	$2$ -[ $^{18}$ F]-FdFuc	Energy metabolism	Nucleophilic	Tumour bearing rats: (AH109A, YS, KEG1).	atio =	Values of tumour: tissue are an average over five cell lines	113 Soc Re

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Cite		Rev														'	utoria		view
	Ref.	114	114	80	1116	1117	120	123	123	123	127	133	136	139	140	142	146	. 164	165
	Comments	Tumour uptake ratio was only above 1.0 for brain and 114 muscle. Tracer was quickly excreted to the kidney.	Tumour uptake ratio was above 1.0 for blood, heart, spleen and muscle, Tracer was quickly excreted to the kidney.	Values as high as 30.7 fold higher uptake observed in inferted over normal risens	because the blodder	Tracer binds in the PAPP 117	expression and inhibited by lactose administration. Selective for peritumoral tissue over background pan-	creatic tissue. Successfully translocated	Successfully translocated	Successfully translocated	Uptake was reported in a linear and time dependent manner. By comparison mammalian cells showed no annewighten the second supports of the companion of the comp	approcessor upgance.  Tracer accumulation was 2-fold higher in leg injected with bacteria than the healthy leg at all three time managed traces are manifested.	Points measured. Tracer specific for bacterial cens. <sup>14</sup> C labelled maltose uptake was blocked by co- administration of the tracer.	More efficient at bacterial imaging than $2-{}_1^{13}\mathrm{F}$ ]-FDG. Selective uptake in $E.~coli$ over mutant strain and	mannianan cens. Tracer was accumulated in infected muscle 3.5 fold in	comparison to un-infected contralateral muscle Stable in human blood serum (>120 min)	SUV (brain) > 0.4 Brain: Low uptake in the brain compared with previous stublood ratio = 0.03 dies. High uptake in the heart could lead to complication in the heart could lead to complication.		Poor interaction with five hNTs suggests β-5-[ <sup>18</sup> F]-FAZR 165 is not transported into human cells efficiently.
	Measurement	Tumour: muscle ratio = 1.33  Tumour: brain ratio (60 min) = 3.71 rimour: muscle ratio (60 min) = 2.74	Tumour: brain ratio (60 min) = 10.16 Tumour: blood ratio (60 min) = 1.12 Tumour: spleen ratio (60 min) = 1.55 Tumour: spleen ratio (60 min) = 1.55	min) = 1.46 Immunosuppressed Balb/ Infected muscle: normal miscle (130 min) = 8 90		I	Peritumoral tissue: mus-	cie ratio = 12.64 	1	ı	I	I	I	— ı	I	I	SUV (brain) $> 0.4$ Brain: blood ratio = $0.03$	Tumour: brain ratio = 5.3	I
	Model	Tumour bearing mice: (FM3A, 3LL). FM3A bearing mice	FM3A bearing mice	Immunosuppressed Balb	Rosa-26 mice	Ex vivo mouse tissue	(pancreatic carcinoma) Mouse (Nude, bearing)	Maize plants (zmsut1-m1	Maize plants (zmsut1-m1	Maize plants (zmsut1-m1	z M. smegmatis	Nude mice (infected with Escherichia coli)	Escherichia coli (ATCC33456) (bacterial)	Escherichia coli Escherichia coli (Lamb mutant), man-	Mude mice infected with	Escherichia con Blood serum (human)	Cynomolgus monkey (Non-human primate	Diann) Human (high-grade glioblastoma)	HCT 116 colorectal carcinoma cells
	Labelling Method	Electrophilic	Electrophilic	Reduction of	Enzymatic	Nucleophilic	Nucleophilic	Nucleophilic	Nucleophillic	Nucleophilic	Chemoenzymatic M. smegmatis	Nucleophilic	Nucleophilic	Nucleophilic	Nucleophilic	Nucleophilic followed by click	Nucleophilic	Nucleophilic	Nucleophilic
	Target	Glycoconjugate metabo- Electrophilic lism in tumours	Glycoconjugate metabo- lism in tumours	Aspergillus fumigatus	$\beta$ -Galactosidase activity	Pancreatic carcinoma	Pancreatic carcinoma	Maize sucrose transpor-	Maize sucrose transpor-	Maize sucrose transpor-	Mycobacterium tuberculosis	Pathogenic bacteria	Pathogenic bacteria	Pathogenic bacteria e	Pathogenic bacteria	Pathogenic bacteria	Neurodegenerative disease	Hypoxia	Hypoxia
(continued)	l Name	3-[ <sup>18</sup> F]Neu5Ac	2,3-di[ <sup>18</sup> F]Neu5Ac - C2(ax.)/C3(eq.)	$[^{^{18} m F}] ext{-FDS}$	$2'$ -[ $^{18}$ F]-FDL	$\mathrm{Et\text{-}2'\text{-}[^{18}\mathrm{F}]\text{-}FDL}$	1'-[ <sup>18</sup> F]-FEL	1'-[ <sup>18</sup> F]-FS	$6'$ -[ $^{18}$ F]-FS	6-[ <sup>18</sup> F]-FS	[ <sup>18</sup> F]-FDTre	6-[ <sup>18</sup> F]- Fluoromaltose	1-[ <sup>18</sup> F]- Fluoromaltose	[ <sup>18</sup> F]- Fluoromaltohexaose	6"-[ <sup>18</sup> F]-	riuoromantriose [ <sup>18</sup> F]AAX21	$[^{18}\mathrm{F}] ext{-GM1}$	$\alpha$ -5'-[ $^{18}$ F]-FAZA	$\beta$ -5'-[ $^{18}$ F]-FAZR
Table (co	Compound no.	32/33	34	36	37	38	39	40	41	42	43	44	45	48	49	20	51	57	28

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Compound no.	.d Name	Target	Labelling Method	Model	Measurement	Comments	Ref.
59	$\beta$ -6'-[ <sup>18</sup> F]-FAZAL	Hypoxia	Nucleophilic	EMT6 tumour bearing	Tumour: muscle ratio	Ratio from hypoxic conditions in comparison to nor-	166
09	$\beta$ -2'-[ <sup>18</sup> F]-FAZA	Hypoxia	Nucleophilic		(120 mm) = 2.13 —		167
61 62	β-3'-['*F]-FAZL [ <sup>18</sup> F]-FDG-2-NIm	Hypoxia Hypoxia	Nucleophilic Nucleophilic	— Wistar rats injected with Walker 256 rat mammary	Uptake in tumour = 0.43 $+$ 0.09% ID ner $\sigma$	— Does not accumulate in tumours or hypoxic tissue	167 168
	,						
63	$[^{^{18} m F}]$ -GAZ	Нурохіа	Nucleophilic	EMT6 tumour bearing	Tumour: muscle ratio (60 min) = $\frac{1}{87}$	Tumour: muscle ratio (60 Evidence suggests not transported in the presence of $\mathbf{p}$ - 169 min) = 1.87	- 169
64	[ <sup>18</sup> F]-FNBG	Tumour detection	Nucleophilic	bearing mice		Tumour: muscle ratio (60 Study compared to [ <sup>18</sup> F]-FAG min) = 4.00 Tumour: blood ratio (60 min) =	170
65	[ <sup>18</sup> F]-FLT	Lymphoma	Nucleophilic	Human	SUV(Aggressive lym-Aggressive lymphoma ps phoma) = 5.9 SUV(Indolent lymphoma) Indolent lymphoma (11) = $\frac{2}{3}$	Aggressive lymphoma patients (21) Indolent lymphoma (11)	180
99	[ <sup>18</sup> F]-FAU	DNA synthesis	Nucleophilic	Dog	Tissue: blood ratio = $\sim 1.0$ Tissue: muscle ratio = $> 1.0$	[ <sup>18</sup> F]-FAU evenly distributed to most organs except higher ratio in excretory pathways (kidney and gallbladder)	183
29	[ <sup>18</sup> F]-FMAU	DNA synthesis	Nucleophilic	Human patients: prostate cancer Breast Cancer		High tumour: background ratios a combination of effi- 186 cient uptake in the tumours and poor uptake in surrounding tissue e.g. brain, bone marrow and pelvis.	- 186
				Recurrent Glioma	Tumour: background = 2.91		
89	$[^{^{1}8}\mathrm{F}] ext{-FEAU}$	DNA synthesis	Nucleophilic	HSV-tk tumour bearing	I	Low uptake, however preferential phosphorylation improves visibility in colon cancer cells	187
69	[ <sup>18</sup> F]-FFAU	DNA synthesis	Nucleophilic	HSV-tk tumour bearing	1	Accumulates significantly in HSV-tk tumours only.	184
70	[ <sup>18</sup> F]-FBAU	DNA synthesis	Nucleophilic	HSV-tk tumour bearing	Tumour: blood ratio (120	Tumour: blood ratio (120 Lower uptake than $[^{18}\mathrm{F}]$ -FMAU	209
71	[ <sup>18</sup> F]-FAC	Deoxyribonucleotide sal- Nucle vage pathway	Nucleophilic	nade nace C57/BL6 mice	Thurth $J = 9.0$ Uptake in spleen = 2.16 $\pm$ 0.48% ID per g Uptake in thymus = 3.29	min.) = 3.0 Uptake in spleen = 2.16 $\pm$ Uptake higher than 2-[ $^{18}$ F]-FDG in spleen. (Not detected 189 Uptake in thymus) Uptake in thymus = 3.29	d 189
72	$5-[^{18}\mathrm{F}]\mathrm{FUR}$	Nucleic acid metabolism Electrophilic	Electrophilic	AH109A tumour bearing	Tumour: blood ratio (60	Rapid clearance from the blood facilitated improved	188
73	$[^{18}{ m F}]{ m FdUR}$	Nucleic acid metabolism Electr	Electrophilic	rats AH109A tumour bearing rats	min) = 3.49 Tumour: blood ratio (60 min) = 6.12	imaging. Rapid clearance from the blood facilitated improved imacing	188
74	[ <sup>18</sup> F]-FXA	Cell proliferation and gene expression	Nucleophilic	HSV-tk tumour bearing nude mice	Tumour: blood ratio (120 min) = $0.47$ Heart: blood ratio (120 min) = $8.15$	Not a suitable tracer for tumour imaging, appears not to 195 be a substrate for HSV-tk.	o 195
75	[ <sup>18</sup> F]-FAA	Cell proliferation and gene expression	Nucleophilic	HSV-tk tumour bearing nude mice	Tumour: blood ratio (120 min) = 2.92 Spleen: blood ratio (120 min) = 3.92	Tumour: blood ratio (120 Moderate tracer for tumour imaging, appears not to be a 195 min) = 2.92 substrate for HSV-tk. Spleen: blood ratio (120 min) = 2.92 substrate for HSV-tk.	a 195
92	[ <sup>18</sup> F]-CFA	Deoxyribonucleotide sal- Nucleophilic vage pathway	Nucleophilic	Human	Absorbed dose co- efficient: Bladder = 2.34E- 01 mGy/MBq	Safe administration in humans, no adverse side effects. 198 Uptake most prominent in bladder, liver, kidneys and spleen.	3. 198

(continued)

Table

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203 Greatest accumulation observed in the kidney, liver and 207 Biodistribution studies showed decreasing uptake from 199 201 <sup>18</sup>F]-FDR has more rapid uptake than 2-[<sup>18</sup>F]-FDG 5 min 202 Tumour: blood ratio (120 Uptake in the kidneys and liver, but rapid clearance mice but 6-[18F]-FDF good selectivity for the tumour 2-[<sup>18</sup>F]-FDG showed greater accumulation in MCF-7 p.i. Stable for 20 min before signal decreases. lung > kidney > heart > spleen.  $[^{18}F]$ -F-AraG crosses the blood brain barrier. Used as a precursor to [18F]-FDR. leads to poor accumulation. Comments MBq Kidneys = 2.51E-02 mGy/Uptake in lung = 9.15  $\pm$ EMT-6 and MCF-7 tumour EMT-6 tumour bearing mice: Tumour: muscle 0.15% ID per g Brain: blood ratio (50 iver = 2.62E-02 mGy $min) = 1.1 \pm 0.2$ Measurement min) = 1.45C3H fibrosarcoma bear-Rats (Sprague-Dawley) A431 tumour bearing bearing BALB/c mice C57BL/6J mice C57BL/6 mice ing mice mouse Hydrolysis of 5'-[<sup>18</sup>F]-FDA<sup>202</sup> Multiple sclerosis lesions Nucleophilic<sup>200</sup> Nucleophilic Nucleophilic Nucleophilic Nucleophilic Enzymatic Labelling Method A<sub>1A</sub>, A<sub>2A</sub>, A<sub>2B</sub> and A<sub>3A</sub> Adenosine receptors. Tumour imaging Fructose uptake via their T cell Ribose salvage accumulation) Breast cancer 5'-[<sup>18</sup>F]-FDA [<sup>18</sup>F]-FDR [18F]-F-AraG  $6-[^{18}F]-FDF$ 1-[<sup>18</sup>F]-FDF [18F]-DFA Name Compound 78

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