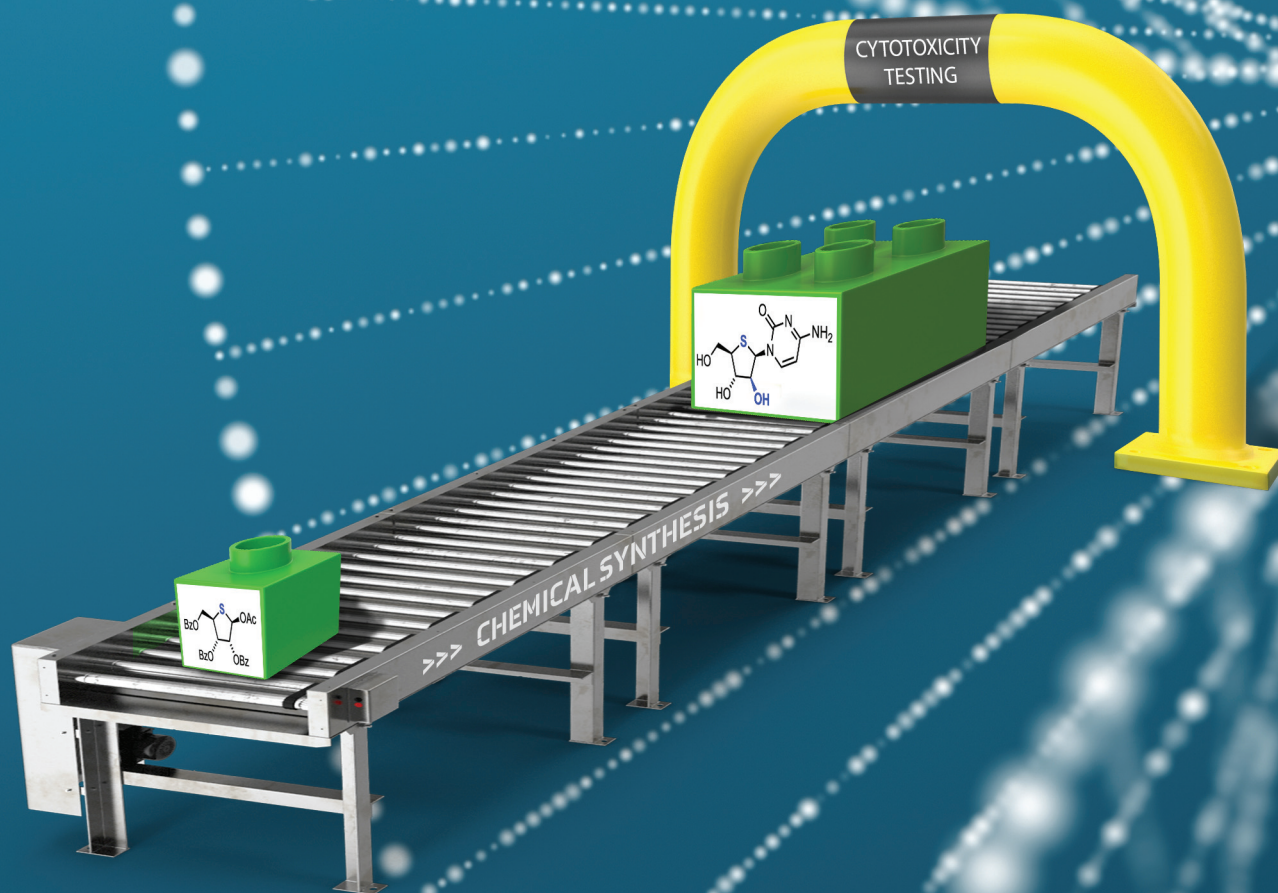


# Organic & Biomolecular Chemistry

Volume 20  
Number 7  
21 February 2022  
Pages 1329-1540

rsc.li/obc



ISSN 1477-0520

**PAPER**

Gavin J. Miller *et al.*  
Chemical synthesis of 4'-thio and 4'-sulfinyl pyrimidine  
nucleoside analogues



Cite this: *Org. Biomol. Chem.*, 2022, **20**, 1401

## Chemical synthesis of 4'-thio and 4'-sulfinyl pyrimidine nucleoside analogues†

Mieke Guinan,<sup>a,b</sup> Ningwu Huang,<sup>c</sup> Chris S. Hawes,<sup>id</sup><sup>a</sup> Marcelo A. Lima,<sup>id</sup><sup>b,d</sup> Mark Smith<sup>c</sup> and Gavin J. Miller<sup>id</sup><sup>\*a,d</sup>

Analogues of the canonical nucleosides required for nucleic acid synthesis have a longstanding presence and proven capability within antiviral and anticancer research. 4'-Thionucleosides, that incorporate bioisosteric replacement of furanose oxygen with sulfur, represent an important chemotype within this field. Established herein is synthetic capability towards a common 4-thioribose building block that enables access to thio-ribo and thio-arabino pyrimidine nucleosides, alongside their 4'-sulfinyl derivatives. In addition, this building block methodology is templated to deliver 4'-thio and 4'-sulfinyl analogues of the established anticancer drug gemcitabine. Cytotoxic capability of these new analogues is evaluated against human pancreatic cancer and human primary glioblastoma cell lines, with observed activities ranging from low  $\mu\text{M}$  to  $>200 \mu\text{M}$ ; explanation for this reduced activity, compared to established nucleoside analogues, is yet unclear. Access to these chemotypes, with thiohemiaminal linkages, will enable a wider exploration of purine and triphosphate analogues and the application of such materials for potential resistance towards relevant hydrolytic enzymes within nucleic acid biochemistries.

Received 26th October 2021,  
Accepted 11th November 2021

DOI: 10.1039/d1ob02097h

rsc.li/obc

### 1. Introduction

A significant proportion of current chemotherapeutic treatments for cancer involve the use of anti-metabolites, particularly modified nucleoside analogues that possess a capability to mimic native purine or pyrimidine nucleosides, which can disrupt metabolic and regulatory pathways.<sup>1</sup> Notwithstanding this significant medicinal capability, therapeutic intervention using nucleoside analogues is often limited by poor cellular uptake, low conversion to the active triphosphate metabolite, rapid degradation or clearance and development of resistance profiles in certain cell types.<sup>2</sup> Consequently, research activity in this field continues to develop syntheses for next generations of nucleoside analogues that can overcome these limitations and provide new therapeutic options.<sup>3–5</sup>

Within this context, 4'-thionucleosides, where the furanose ring oxygen is substituted with sulfur, have received attention from several academic and industrial groups since a first dis-

closure of 4'-thioadenosine in the early 1960s;<sup>6,7</sup> Fig. 1 highlights some key achievements in this area. Bioisosteric replacement of furanose oxygen with larger sulfur seeks to explore the biological effect imparted through changes to furanose ring conformation and the hydrolytic stability of a thiohemiaminal glycosidic linkage.

Insertion of a sulfur atom to access thiofuranose components generally start from available chiral pool materials and the use of thiourea to convert 4,5-epoxides to 4,5-thiiranes,<sup>8,9</sup> alongside sodium sulfide-mediated formation of 2,5-bicyclic systems are notable examples of key intermediates developed to enable this.<sup>10–12</sup> Open chain systems have also been used,<sup>13</sup> for example, effecting double displacement of a 1,4-bismesylate with  $\text{Na}_2\text{S}$  to access 1-deoxy thiofuranoses,<sup>14</sup> and both C1 aldehyde and thioacetal oxidation levels have delivered access to anomeric thioglycosides.<sup>15,16</sup> Two main approaches have been adopted to install appropriate nucleobases; firstly thioglycosylation of a silylated nucleobase,<sup>8,17</sup> and, secondly a Pummerer-type reaction of the sulfoxide to condense with a corresponding nucleobase.<sup>16,18</sup> Hypervalent iodine reagents have also been used to effect a similar transformation.<sup>19</sup>

As part of a program exploring chemical synthesis approaches to next generation nucleoside scaffolds, we were interested in accessing appropriate 4'-thionucleosides and templating this bioisosteric replacement onto established chemotypes, a tactic recently implemented by Liotta and colleagues for 2'-C-methyl-4'-thionucleosides.<sup>20</sup> Herein we report

<sup>a</sup>Lennard-Jones Laboratory, School of Chemical and Physical Sciences, Keele University, Keele, Staffordshire ST5 5BG, UK. E-mail: g.j.miller@keele.ac.uk

<sup>b</sup>School of Life Sciences, Keele University, Keele, Staffordshire ST5 5BG, UK

<sup>c</sup>Riboscience LLC, 428 Oakmead Pkwy, Sunnyvale, CA 94085, USA

<sup>d</sup>Centre for Glycoscience Research, Keele University, Keele, Staffordshire ST5 5BG, UK

† Electronic supplementary information (ESI) available. CCDC 2115322. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d1ob02097h



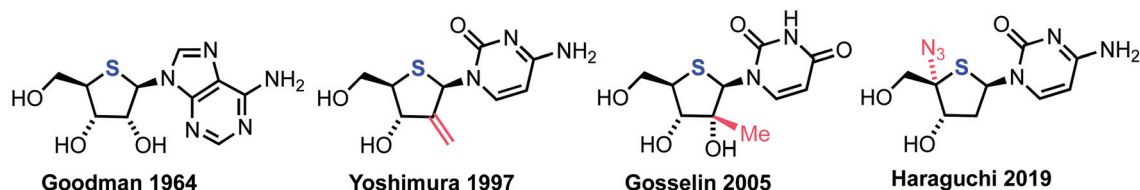


Fig. 1 Historical and current examples of thionucleosides (blue sulphur) with additional ring substituent modifications (red).

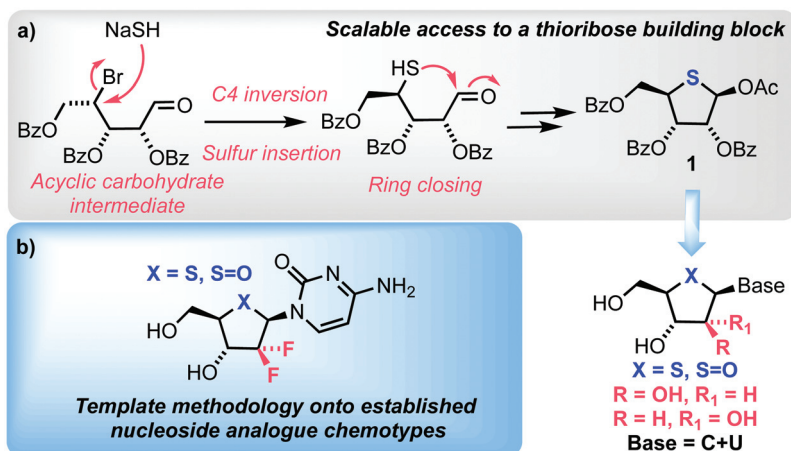


Fig. 2 (a) Strategy to access 4-thioribose derivative 1 as a key intermediate for 4'-thionucleoside synthesis and (b) potential thereof to template to established nucleoside analogue classes (blue box).

our synthesis of 4'-thio and 4'-sulfinyl nucleosides; we targeted an open-chain C1-oxime to enable sulfur inclusion using displacement of an appropriate 4-position leaving group, with concomitant ring closure onto a C1 aldehyde. This was intended to provide a benchmark in then accessing related 2'-deoxy-2',2'-gem-difluoro and *D-arabino* structures which, alongside recent examples 2'-deoxy-2'-fluoro and *L*-3'-deoxy-3',3'-difluoro systems,<sup>13,21,22</sup> provides capability to more broadly study 4'-thionucleoside chemotypes and their structure activity relationships. These aims are highlighted in Fig. 2.

## 2. Results and discussion

### 2.1. Synthesis of a 4-thioribose building block and extension to a 2-deoxy-2,2-difluoro-4-thioribose analogue

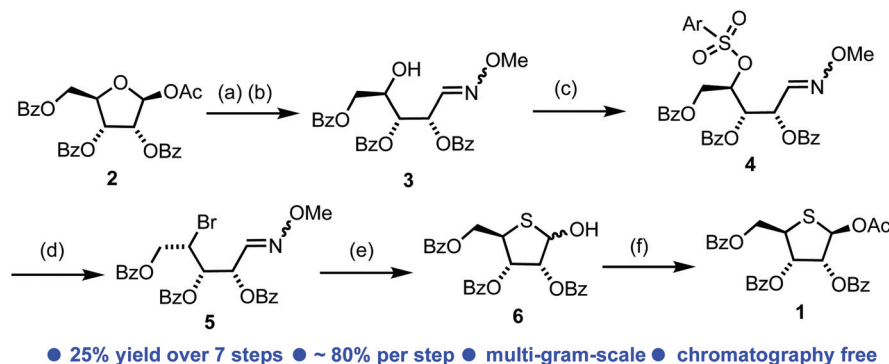
In order to access our intended series of thionucleoside derivatives, a scalable and reliable method for the synthesis of 4-thio-*D*-ribofuranose 1 was required (Scheme 1). Starting from commercially available 2, the anomeric acetate was hydrolysed using H<sub>2</sub>O/BF<sub>3</sub>·OEt<sub>2</sub> in 91% yield on 100 g scale. The resultant hemi-acetal was used crude and converted to the corresponding oxime 3 *via* treatment with *O*-methoxyhydroxylamine hydrochloride and Et<sub>3</sub>N. This material was isolated as a mixture of oxime isomers (3/1 ratio) in 90% yield, again on multigram scale. Manipulation of the C4 position in 3 to facilitate conversion to the final thiofuranose, with retention of the

*C4-ribo*-configuration, was explored next. Direct halogenation and inversion of stereochemistry at C4 using CBr<sub>4</sub> or Br<sub>2</sub> with PPh<sub>3</sub> proved unsuccessful, returning only starting material. Instead, the C4-OH in 3 was converted to an arylsulfonyl leaving group. Initially here we targeted a 4-nitrobenzenesulfonate, but persistent low yields (maximum obtained = 31%) and a requirement for chromatography led us to explore other options. An earlier report of a less common 2,3,5-trichlorobenzene sulfonate proved fruitful,<sup>23</sup> delivering 4 in 72% yield. Purification of 4 was achieved using trituration from Et<sub>2</sub>O, enabling easy isolation as a white solid. This material could be prepared in multigram amounts in 56% overall yield for three steps from 2 and required no column chromatography.

Nucleophilic displacement of the 4-sulfonyl group within 4 was explored using LiBr in a Finkelstein-type reaction. The use of DMI/THF as the solvent at 60 °C for 16 h resulted in a mixture of C4 diastereoisomers (3/1, *S/R*, see ESI Fig. S4†), presumably forming *via* a second nucleophilic displacement of bromide 5 to give the unwanted the C4-*R* epimer. Similar issues surrounding unwanted C4 epimerisation were encountered by Codée and co-workers during their synthesis of 4-thiofuranosides.<sup>14</sup> Reducing the reaction time to 2 h in the same solvent system improved the diastereomeric outcome (10/1, *S/R*), however, this was accompanied by incomplete consumption of 4. Switching solvent to 2-butanone and heating at 80 °C for 18 h delivered diastereomerically pure C4-bromide 5 in 89% yield. <sup>13</sup>C NMR analysis of 5 confirmed an upfield shift of







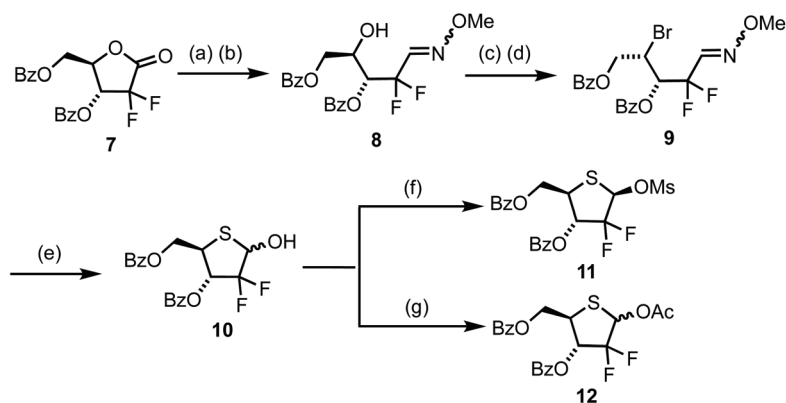
**Scheme 1** (a)  $\text{BF}_3 \cdot \text{Et}_2\text{O}$ ,  $\text{H}_2\text{O}$ , MeCN, rt, 91%; (b)  $\text{H}_2\text{N} \cdot \text{OMe} \cdot \text{HCl}$ ,  $\text{Et}_3\text{N}$ , MeOH, rt, 90%; (c) 2,4,5-Trichlorobenzene sulfonyl chloride, *N*-methylimidazole, MeCN, rt, 72%; (d) LiBr, butanone, 80 °C, 89%. (e) (i) Glyoxylic acid, MeCN, 70 °C, 92%; (ii) NaSH- $\text{H}_2\text{O}$ ,  $\text{H}_2\text{O}$ , DMF, 0 °C, 76%; (f) DMAP,  $\text{Ac}_2\text{O}$ , rt, 72% ( $\beta$ -only); Ar = 2,4,5-trichlorophenyl.

C4 to  $\delta_{\text{C}}$  47.8 ppm, from  $\delta_{\text{C}}$  79.6 ppm. Treatment of bromide **5** with glyoxylic acid at 70 °C effected hydrolysis of the oxime to the corresponding aldehyde in 92% yield, which was used immediately for conversion to the desired 4-thiofuranose **6**. This proceeded *via* reaction with NaSH, effecting  $\text{S}_{\text{N}}2$  displacement of the C4 bromide followed by ring closure onto the C1-aldehyde, obtaining **6** as a mixture of anomers in 76% yield. Crude **6** was treated with  $\text{Ac}_2\text{O}$  in pyridine with catalytic DMAP to obtain the acetylated product **1** as a mixture of anomers (4/1,  $\beta/\alpha$ ). Simple trituration from MeOH isolated the  $\beta$ -anomer of **1** exclusively in a satisfactory 50% yield from **5**, with analytical data confirming those reported previously for *D*-ribo thiofuranoses.<sup>9</sup> The development of this synthetic route to **1** required no column chromatography and was completed starting from 100 g of **2**, delivering **1** in an overall yield of 25% for the seven steps and in 25 g quantity.

The chemistry developed in Scheme 1 was next mapped onto a 2-deoxy-2,2-*gem*-difluoro ribose system to access 4'-thio-gemcitabine and analogues thereof (Scheme 2). Commercially available lactone **7** was manipulated in six steps to deliver 2-deoxy-2,2-difluoro-1-(4-thio-*D*-ribofuranose) **10**. Lactone **7** was

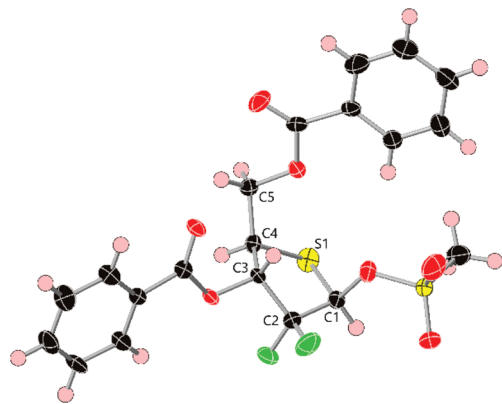
first reduced using  $\text{Li}(\text{O}^t\text{Bu})_3\text{AlH}$  to the hemiacetal in 95% crude yield and then converted directly to oxime **8** *via* reaction with *O*-methoxyhydroxylamine and  $\text{Et}_3\text{N}$  in the presence of pyridinium *p*-toluenesulfonate. Interestingly, no reaction to convert the intermediate hemiacetal was observed in the absence of the pyridinium salt. Oxime **8** then underwent successive derivatisation at C4, first to the sulfonate ester and then nucleophilic substitution to yield bromide **9**. Finally, oxime hydrolysis was followed by incorporation of sulfur at C4 to restore the *D*-ribo configuration and subsequent cyclisation to thiohemiacetal **10**. This enabled access to multigram quantities of **10** in 6 steps and 56% overall yield from the commercial starting material.

The anomeric hydroxyl group in **10** was next converted to either mesylate **11** or acetate **12** as appropriate leaving groups to explore glycosylation of nucleobases. Treatment of **10** with MsCl and  $\text{Et}_3\text{N}$  (Scheme 2) afforded **11** in 79% yield as a 1/4,  $\alpha/\beta$  mixture. The  $\beta$ -anomer was isolated by crystallisation from hot  $\text{Et}_2\text{O}$  and the resultant solid recrystallised by diffusion using  $\text{CH}_2\text{Cl}_2$ /hexanes to afford pure  $\beta$ -**11**. A sample of  $\beta$ -**11** was analysed by X-ray crystallography and confirmed the



**Scheme 2** (a)  $\text{Li}(\text{O}^t\text{Bu})_3\text{AlH}$ , THF, 0 °C, 95%; (b)  $\text{H}_2\text{N} \cdot \text{OMe} \cdot \text{HCl}$ ,  $\text{Et}_3\text{N}$ , MeCN,  $\text{H}_2\text{O}$ , pyridinium *p*-toluenesulfonate, rt, 90% (c) 2,4,5-Trichlorobenzene sulfonyl chloride, *N*-methylimidazole, MeCN, rt, 75% (d) LiBr, butanone, 80 °C. (e) (i) Glyoxylic acid, MeCN, 70 °C (ii) NaSH- $\text{H}_2\text{O}$ ,  $\text{H}_2\text{O}$ , DMF, 0 °C, 97% over 3 steps (f) MsCl,  $\text{Et}_3\text{N}$ ,  $\text{CH}_2\text{Cl}_2$ , rt, 79% (53% for  $\beta$ -anomer only) (g)  $\text{Ac}_2\text{O}$ ,  $\text{Et}_3\text{N}$ ,  $\text{CH}_2\text{Cl}_2$ , rt, 88%.





**Fig. 3** X-ray crystal structure of  $\beta$ -**11** with numbering scheme for core atoms. ADPs are rendered at 50% probability level and ring disorder on the C5 phenyl ester substituent is omitted for clarity. Atom colouring scheme: black = carbon, red = oxygen, green = fluorine, yellow = sulfur, pink = hydrogen.

double stereochemical inversion at C4, which retained a *D-ribo* configuration (Fig. 3). The anomeric mesylate and C5 were observed above the plane of the thiopyranose ring, consistent with 1- $\beta$ -*D-ribo* stereochemistry, with the ring adopting a C3-*endo* conformation in the solid state. Anomeric acetate **12** was accessed in 88% yield as a 3/2 mixture of anomers that, in our hands, proved inseparable by crystallisation or column chromatography.

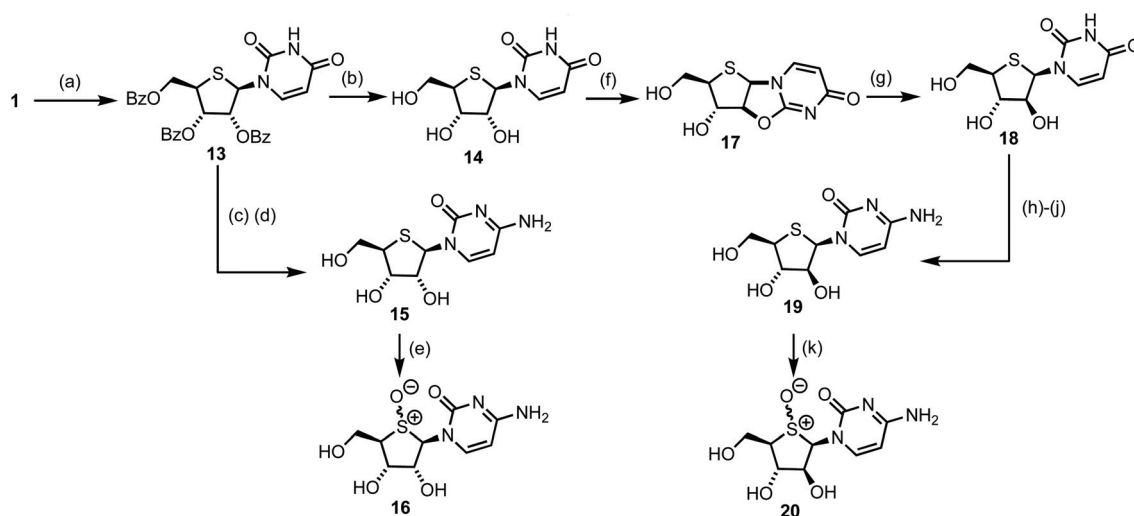
## 2.2. Synthesis of 4'-thioribo- and 4'-thioarabino nucleosides

With access to multigram scale quantities of **1**, a series of 4'-thioribo and 4'-thioarabino pyrimidines were targeted. A pathway to access these was proposed from 4'-thiouridine **14** (Scheme 3). Comparative literature for the synthesis of 2',3',5'-tri-*O*-benzoyl protected uridine involved refluxing the reactants

for 3 h in acetonitrile, following silylation of the nucleobase.<sup>24</sup> However, reaction under these conditions for **1** produced low yields of **13** (20–30%). By conducting the reaction just below the boiling point of MeCN, at 75 °C, the yield improved significantly, to 74%. The  $\beta$ -anomer of **13** formed preferentially (<sup>1</sup>H NMR of crude **13** indicated a 10/1,  $\beta/\alpha$  ratio, [<sup>3</sup>J<sub>H1-H2</sub> = 6.8 Hz for  $\beta$ -**13**]) and the reaction was scalable to 10 g.<sup>25</sup>

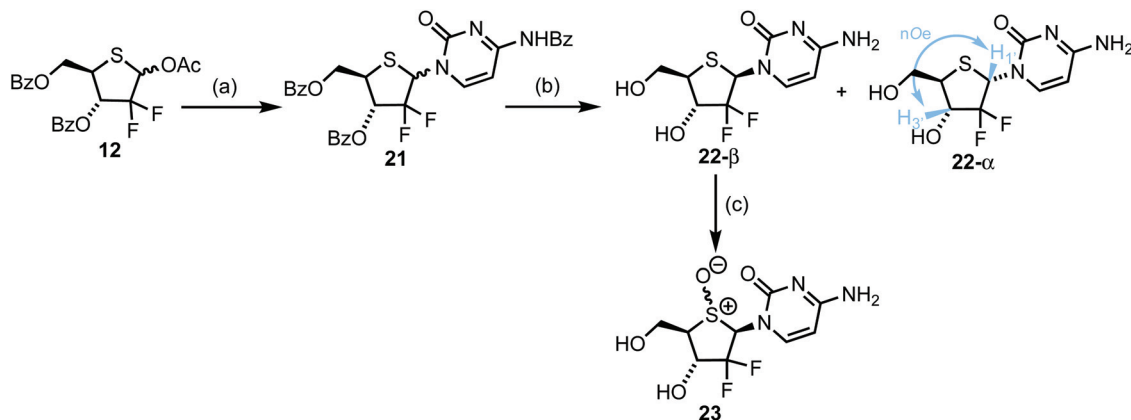
Global deprotection of **13** was completed using 7 M NH<sub>3</sub> in MeOH to obtain 4'-thiouridine **14** in 96% yield. This material was next converted to its cytosine form, first by treatment of **14** with POCl<sub>3</sub> and then 1,2,4-triazole to furnish the heterocyclic intermediate, before a final treatment with NH<sub>3</sub> in MeOH concomitantly substituted the triazole and removed the benzoyl protecting groups to give 4'-thiocytidine **15** in 77% yield over two steps.

4'-thiouridine **14** was also converted to its C2' epimer **18** *via* an intramolecular cyclisation of the C4-carbonyl, displacing a C2'-carbonate leaving group. This inverted the C2' stereochemistry to give  $\beta$ -1',2'-*syn*-bicycle **17** in 92% yield, with <sup>13</sup>C NMR confirming a chemical shift change of  $\delta_C$  152.3 ppm to  $\delta_C$  175.4 ppm for C2' in **17**. Subsequent ring opening of **17** was achieved by stirring with KOH in EtOH/H<sub>2</sub>O, to give C2'-*arabino* configured **18** in almost quantitative yield. The observed <sup>1</sup>H NMR coupling constant between H2' and H3' for **18** (<sup>3</sup>J<sub>H2'-H3'</sub> = 9.1 Hz) was significantly different than that observed for **14** (<sup>3</sup>J<sub>H2'-H3'</sub> = 3.7 Hz), supporting inversion of stereochemistry at C2'. 4'-thioarabinouridine **18** was also converted to its cytosine form using the method previously established for **15**, delivering 4'-thioarabincytidine **19** in 52% yield over three steps from **18**. Earlier efforts to directly convert **15** to **19** *via* a  $\beta$ -1',2'-*syn*-intermediate bi-cycle were unsuccessful; multiple reaction products were observed and this conversion was abandoned. Finally, the corresponding sulfoxides of **15** and **19** were prepared *via* treatment with 1.5 equivalents of *m*-CPBA, to afford novel **16** and **20** in 90% and 78% yields



**Scheme 3** (a) (i) Uracil, HMDS, reflux (ii) TMSOTf, MeCN, 75 °C, 74% (b) 7 M NH<sub>3</sub> in MeOH, MeOH, 40 °C, 96% (c) POCl<sub>3</sub>, 1,2,4-triazole, Et<sub>3</sub>N, MeCN, rt (d) NH<sub>4</sub>OH, 1,4-dioxane, rt, then 7 M NH<sub>3</sub> in MeOH, MeOH, 40 °C, 77%, 2 steps from **13** (e) *m*-CPBA, H<sub>2</sub>O, MeCN, 0 °C, 90%, 1/1 d.r. at S (f) (PhO)<sub>2</sub>CO, NaHCO<sub>3</sub>, DMF, 100 °C, 98% (g) KOH, EtOH, H<sub>2</sub>O, rt, 90% (h) Ac<sub>2</sub>O, DMAP, pyridine, rt, 82% (i) POCl<sub>3</sub>, 1,2,4-triazole, Et<sub>3</sub>N, MeCN, rt (j) 7 M NH<sub>3</sub> in MeOH, MeOH, 120 °C, 70%, 2 steps from **18** (k) *m*-CPBA, H<sub>2</sub>O, MeCN, 0 °C, 78%, 2.5/1 d.r. at S.





**Scheme 4** (a) *N*<sup>4</sup>-Benzoyl cytosine, HMDS, pyridine, SnCl<sub>4</sub>, DCE, reflux, 28% (25% returned **12**), 1/1,  $\alpha/\beta$ , then fractional precipitation, 10% for **21- $\alpha$** , 6% for **21- $\beta$** . (b) From **21- $\alpha/\beta$** , NH<sub>3</sub>, MeOH, 40 °C, 96% crude, then preparative HPLC, 44% for **22- $\alpha$** , 34% for **22- $\beta$** ; From **21- $\beta$** , NH<sub>3</sub>, MeOH, 63% (c) *m*-CPBA, H<sub>2</sub>O, MeCN, 15%, 4/1 d.r. at S.

respectively. <sup>13</sup>C NMR analysis confirmed a significant downfield shift of C1' and C4' from  $\delta_C$  65.1 and 51.7 ppm in **16** to  $\delta_C$  73.1 and 65.7 ppm in **20** respectively. Attempted separation of the *S*-diastereoisomers by crystallisation and reverse phase preparative HPLC were unsuccessful.

### 2.3. Synthesis of 4'-thio and 4'-sulfinylgemcitabine

In order to access 2-deoxy-2,2-*gem*-difluorothionucleosides, we returned to anomeric acetate **12** and mesylate **11** to investigate nucleobase attachment. Prior reports suggested use of an anomeric mixture of **11** delivered the corresponding nucleosides as a 1/1,  $\alpha/\beta$  mixture, regardless of the anomeric ratio of the starting mesyl glycoside.<sup>10,26</sup> In order to target 4'-thiogemcitabine, silylated *N*<sup>4</sup>-benzoyl cytosine was first glycosylated with donor **11**, using TMSOTf as activator. These conditions were unsuccessful (no product was isolated) and SnCl<sub>4</sub> was selected instead. Under these conditions the desired nucleoside was isolated, but in <10% yield. Accordingly, we switched glycosyl donor to anomeric acetate **12** and were pleased to observe an improved yield for glycosylation of silylated *N*<sup>4</sup>-benzoyl cytosine, delivering **21** in 28% yield, with 25% of **12** recovered. Expectedly, no diastereocontrol was observed for this glycosylation; **21** was isolated as a 1.1/1 anomeric mixture, requiring subsequent separation either using fractional precipitation or preparative HPLC. Following protecting group removal, **22- $\alpha$**  was confirmed through selective 1D NOESY, where through-space dipolar interactions between H<sub>1</sub> and H<sub>3</sub> were observed (Scheme 4 and ESI Fig. S5†). Anomer **22- $\beta$**  was then oxidised at sulfur to afford the 4'-sulfinyl derivative of 4'-thiogemcitabine. Oxidation was confirmed through a significant downfield shift of C1' and C4' from  $\delta_C$  59.7 and 46.3 ppm respectively in **22- $\beta$**  to  $\delta_C$  84.6 and 72.8 ppm respectively in **23**.

### 2.4. Biological Evaluation

Nucleoside analogues **15**, **16**, **19**, **20**, **22- $\beta$**  and **23** were evaluated in cytotoxicity assays against human pancreatic cancer (PANC-1) and human primary glioblastoma (U87-MG) cells

**Table 1** Cytotoxicity data for **19**, Ara-C and Gemcitabine in U87-MG and PANC-1 cells

Entry	Compound	CC <sub>50</sub> (μM) U87-MG	CC <sub>50</sub> (μM) PANC-1
1	Ara-C	0.19	0.43
2	Gemcitabine	0.01	0.21
3	<b>19</b>	0.59	12.0

and their CC<sub>50</sub> values compared to commercial arabinocytidine (Ara-C) and gemcitabine (Table 1). Only analogue **19** displayed measurable cytotoxicity, with a CC<sub>50</sub> value of 0.59 μM in U87-MG cells and 12 μM in PANC-1 cells (entry 3, Table 1); all other analogues had CC<sub>50</sub> values >200 μM. The data for **19** were not immediately comparable to Ara-C or gemcitabine, as both displayed superior CC<sub>50</sub> values in the cell lines evaluated (entries 1 and 2, Table 1). These results suggest that a thio *arabino* chemotype may impart some degree of cytotoxicity, but that replacement of furanose oxygen with sulfinyl is not tolerated.

## 3. Conclusions

We have developed a scalable and column chromatography free synthesis of a protected 4-thioribose intermediate. This synthetic methodology has also been adapted for a multigram preparation of 2-deoxy-2-*gem*-difluoro 4-thioribose analogues. These building blocks enable entry to a range of pyrimidine-based 4'-thionucleoside analogues, including first examples of 4'-sulfinyl derivatives of *ribocytidine*, Ara-C and gemcitabine.

From the compounds synthesised, 4'-thioarabinocytidine was shown to have moderate cytotoxicity towards U87-MG cells, but generally all the thionucleosides evaluated showed little cytotoxicity. This is most likely due to the compounds being poor substrates for nucleotide-forming kinases,<sup>27</sup> essential for converting to the active triphosphate. Alternatively, the



thionucleoside triphosphates might not be substrates for human polymerases. Further work to access monophosphate prodrug forms of these analogues is currently underway and will be reported in due course.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

Keele University and Riboscience LLC are thanked for PhD studentship funding to M. G. UK Research and Innovation (UKRI, Future Leaders Fellowship, MR/T019522/1) are thanked for project grant funding to G. J. M.

## References

- L. P. Jordheim, D. Durantel, F. Zoulim and C. Dumontet, *Nat. Rev. Drug Discovery*, 2013, **12**, 447–464.
- C. Galmarini, J. Mackey and C. Dumontet, *Leukemia*, 2001, **15**, 875–890.
- M. Guinan, C. Benckendorff, M. Smith and G. J. Miller, *Molecules*, 2020, **25**, 2050.
- M. Meanwell, S. M. Silverman, J. Lehmann, B. Adluri, Y. Wang, R. Cohen, L.-C. Campeau and R. Britton, *Science*, 2020, **369**, 725–730.
- G. J. Miller, *Science*, 2020, **369**, 623.
- E. J. Reist, D. E. Gueffroy and L. Goodman, *J. Am. Chem. Soc.*, 1964, **86**, 5658–5663.
- M. Betson, N. Allanson and P. Wainwright, *Org. Biomol. Chem.*, 2014, **12**, 9291–9306.
- D. Dukhan, E. Bosc, J. Peyronnet, R. Storer and G. Gosselin, *Nucleosides, Nucleotides Nucleic Acids*, 2005, **24**, 577–580.
- Z.-H. Sun and B. Wang, *J. Org. Chem.*, 2008, **73**, 2462–2465.
- Y. Yoshimura, K. Kitano, K. Yamada, H. Satoh, M. Watanabe, S. Miura, S. Sakata, T. Sasaki and A. Matsuda, *J. Org. Chem.*, 1997, **62**, 3140–3152.
- Y. Yoshimura, K. Kitano, H. Satoh, M. Watanabe, S. Miura, S. Sakata, T. Sasaki and A. Matsuda, *J. Org. Chem.*, 1996, **61**, 822–823.
- Y. Yoshimura, Y. Saito, Y. Natori and H. Wakamatsu, *Chem. Pharm. Bull.*, 2018, **66**, 139–146.
- S. Dostie, M. Prévost, P. Mochirian, K. Tanveer, N. Andrella, A. Rostami, G. Tambutet and Y. Guindon, *J. Org. Chem.*, 2016, **81**, 10769–10790.
- J. M. Madern, T. Hansen, E. R. van Rijssel, H. A. V. Kistemaker, S. van der Vorm, H. S. Overkleeft, G. A. van der Marel, D. V. Filippov and J. D. C. Codée, *J. Org. Chem.*, 2019, **84**, 1218–1227.
- I. Birtwistle, P. Maddocks, J. M. O'Callaghan and J. Warren, *Synth. Commun.*, 2001, **31**, 3829–3838.
- T. Naka, N. Minakawa, H. Abe, D. Kaga and A. Matsuda, *J. Am. Chem. Soc.*, 2000, **122**, 7233–7243.
- K. Haraguchi, H. Kumamoto, K. Konno, H. Yagi, Y. Tatano, Y. Odanaka, S. S. Matsubayashi, R. Snoeck and G. Andrei, *Tetrahedron*, 2019, **75**, 4542–4555.
- I. O'Neil and K. Hamilton, *Synlett*, 1992, 791–792.
- N. Nishizono, R. Baba, C. Nakamura, K. Oda and M. Machida, *Org. Biomol. Chem.*, 2003, **1**, 3692–3697.
- Z. W. Dentmon, T. M. Kaiser and D. C. Liotta, *Molecules*, 2020, **25**, 5165.
- F. Zheng, X.-H. Zhang, X.-L. Qiu, X. Zhang and F.-L. Qing, *Org. Lett.*, 2006, **8**, 6083–6086.
- M. Takahashi, S. Daidouji, M. Shiro, N. Minakawa and A. Matsuda, *Tetrahedron*, 2008, **64**, 4313–4324.
- K. Nakamura, S. Shimamura, J. Imoto, M. Takahashi, K. Watanabe, K. Wada, Y. Fujino, T. Matsumoto, M. Takahashi and H. Okada, *et al.*, *Intermediate for Synthesis of 1-(2-Deoxy-2-Fluoro-4-Thio-Beta-D-Arabinofuranosyl) Cytosine, Intermediate for Synthesis of Thionucleoside, and Methods for Producing These Intermediates*, EP 2,883,866A1, 2013.
- H. Shirouzu, H. Morita and M. Tsukamoto, *Tetrahedron*, 2014, **70**, 3635–3639.
- M. Guinan, D. Lynch, M. Smith and G. J. Miller, in *Carbohydrate Chemistry: Proven Synthetic Methods*, CRC Press, 2020, vol. 5, pp. 227–232.
- K. Brown, M. Dixey, A. Weymouth-Wilson and B. Linclau, *Carbohydr. Res.*, 2014, **387**, 59–73.
- N. L. Golitsina, F. T. Danehy, R. Fellows, E. Cretton-Scott and D. N. Standring, *Antiviral Res.*, 2010, **85**, 470–481.

