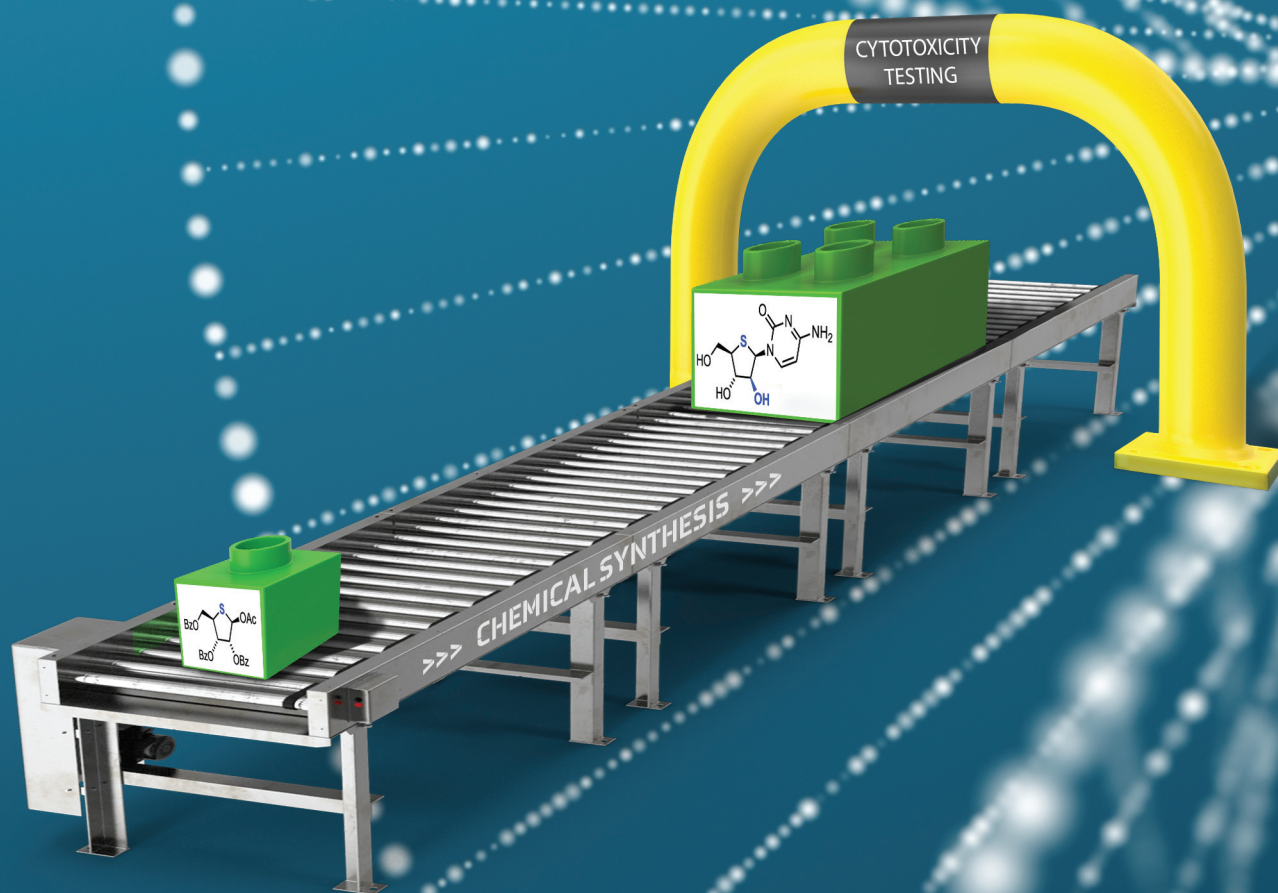


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Chemical synthesis of 4'-thio and 4'-sulfinyl pyrimidine nucleoside analogues†

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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 μM 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.

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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.¹ 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.² 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.^{3–5}

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;^{6,7} 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,^{8,9} alongside sodium sulfide-mediated formation of 2,5-bicyclic systems are notable examples of key intermediates developed to enable this.^{10–12} Open chain systems have also been used,¹³ for example, effecting double displacement of a 1,4-bismesylate with Na_2S to access 1-deoxy thiofuranoses,¹⁴ and both C1 aldehyde and thioacetal oxidation levels have delivered access to anomeric thioglycosides.^{15,16} Two main approaches have been adopted to install appropriate nucleobases; firstly thioglycosylation of a silylated nucleobase,^{8,17} and, secondly a Pummerer-type reaction of the sulfoxide to condense with a corresponding nucleobase.^{16,18} Hypervalent iodine reagents have also been used to effect a similar transformation.¹⁹

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.²⁰ Herein we report

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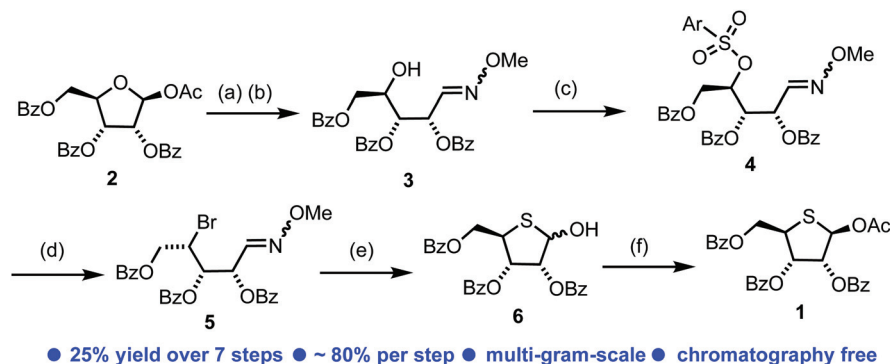
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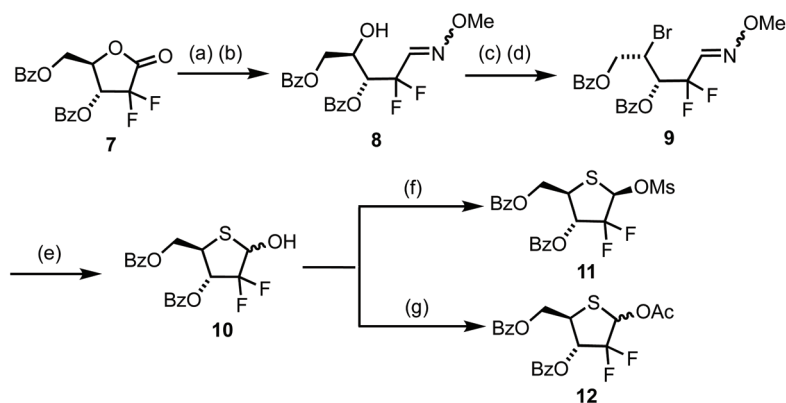
Scheme 1 (a) $\text{BF}_3 \cdot \text{Et}_2\text{O}$, H_2O , MeCN, rt, 91%; (b) $\text{H}_2\text{N-OMe-HCl}$, Et_3N , MeOH, rt, 90%; (c) 2,4,5-Trichlorobenzenesulfonyl chloride, *N*-methylimidazole, MeCN, rt, 72%; (d) LiBr, butanone, 80 °C, 89%. (e) (i) Glyoxylic acid, MeCN, 70 °C, 92%; (ii) NaSH- H_2O , H_2O , DMF, 0 °C, 76%; (f) DMAP, Ac_2O , rt, 72% (β -only); Ar = 2,4,5-trichlorophenyl.

C4 to δ_{C} 47.8 ppm, from δ_{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 Ac_2O in pyridine with catalytic DMAP to obtain the acetylated product **1** as a mixture of anomers (4/1, β/α). Simple trituration from MeOH isolated the β -anomer of **1** exclusively in a satisfactory 50% yield from **5**, with analytical data confirming those reported previously for *D-ribo* thiofuranoses.⁹ 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 Et_3N 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 Et_3N (Scheme 2) afforded **11** in 79% yield as a 1/4, α/β mixture. The β -anomer was isolated by crystallisation from hot Et_2O and the resultant solid recrystallised by diffusion using CH_2Cl_2 /hexanes to afford pure β -**11**. A sample of β -**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) $\text{H}_2\text{N-OMe-HCl}$, Et_3N , MeCN, H_2O , pyridinium *p*-toluenesulfonate, rt, 90% (c) 2,4,5-Trichlorobenzenesulfonyl chloride, *N*-methylimidazole, MeCN, rt, 75% (d) LiBr, butanone, 80 °C. (e) (i) Glyoxylic acid, MeCN, 70 °C (ii) NaSH- H_2O , H_2O , DMF, 0 °C, 97% over 3 steps (f) MsCl, Et_3N , CH_2Cl_2 , rt, 79% (53% for β -anomer only) (g) Ac_2O , Et_3N , CH_2Cl_2 , rt, 88%.



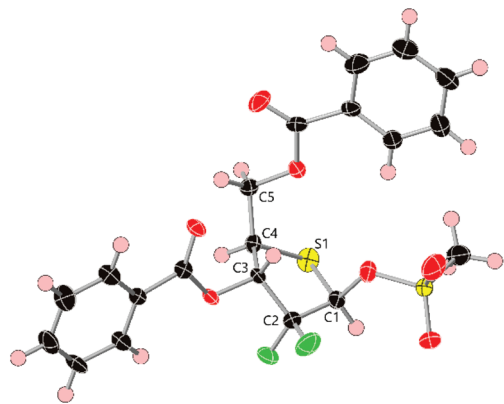


Fig. 3 X-ray crystal structure of β -**11** with numbering scheme for core atoms. ADPs are rendered at 50% probability level and ring disorder on the C5 phenyl ester substituent is omitted for clarity. Atom colouring scheme: black = carbon, red = oxygen, green = fluorine, yellow = sulfur, pink = hydrogen.

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- β -*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.

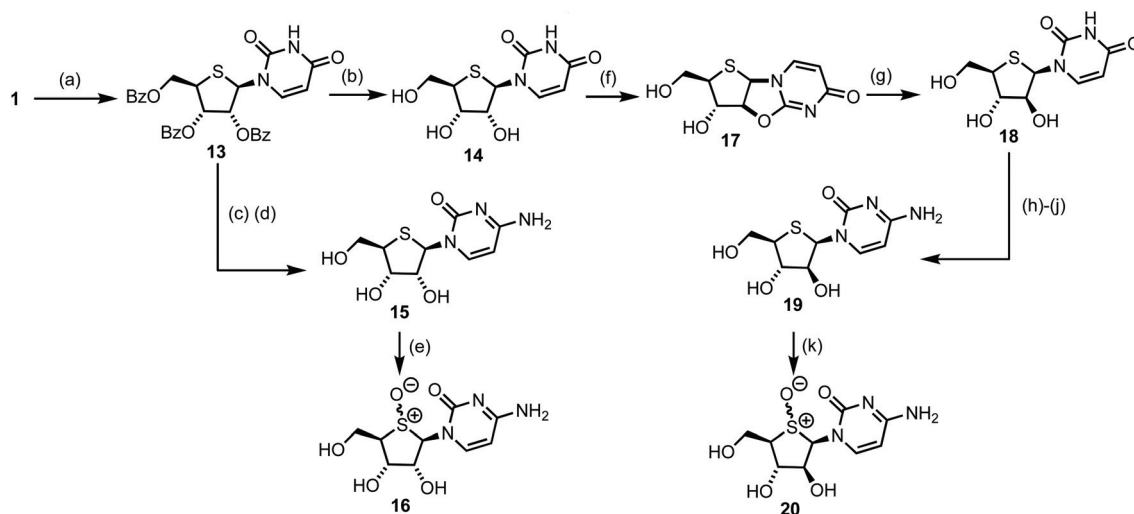
2.2. Synthesis of 4'-thioribo- and 4'-thioarabino nucleosides

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.²⁴ 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 β -anomer of **13** formed preferentially (¹H NMR of crude **13** indicated a 10/1, β/α ratio, [³J_{H1-H2} = 6.8 Hz for β -**13**]) and the reaction was scalable to 10 g.²⁵

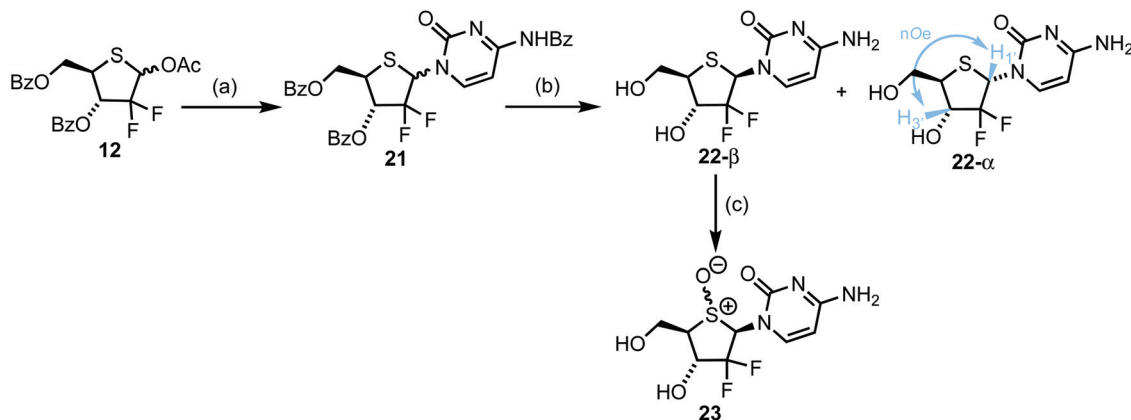
Global deprotection of **13** was completed using 7 M NH₃ in MeOH to obtain 4'-thiouridine **14** in 96% yield. This material was next converted to its cytosine form, first by treatment of **14** with POCl₃ and then 1,2,4-triazole to furnish the heterocyclic intermediate, before a final treatment with NH₃ 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 β -1',2'-*syn*-bicycle **17** in 92% yield, with ¹³C NMR confirming a chemical shift change of δ_C 152.3 ppm to δ_C 175.4 ppm for C2' in **17**. Subsequent ring opening of **17** was achieved by stirring with KOH in EtOH/H₂O, to give C2'-*arabino* configured **18** in almost quantitative yield. The observed ¹H NMR coupling constant between H2' and H3' for **18** (³J_{H2'-H3'} = 9.1 Hz) was significantly different than that observed for **14** (³J_{H2'-H3'} = 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 β -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 NH₃ in MeOH, MeOH, 40 °C, 96% (c) POCl₃, 1,2,4-triazole, Et₃N, MeCN, rt (d) NH₄OH, 1,4-dioxane, rt, then 7 M NH₃ in MeOH, MeOH, 40 °C, 77%, 2 steps from **13** (e) *m*-CPBA, H₂O, MeCN, 0 °C, 90%, 1/1 d.r. at S (f) (PhO)₂CO, NaHCO₃, DMF, 100 °C, 98% (g) KOH, EtOH, H₂O, rt, 90% (h) Ac₂O, DMAP, pyridine, rt, 82% (i) POCl₃, 1,2,4-triazole, Et₃N, MeCN, rt (j) 7 M NH₃ in MeOH, MeOH, 120 °C, 70%, 2 steps from **18** (k) *m*-CPBA, H₂O, MeCN, 0 °C, 78%, 2.5/1 d.r. at S.





Scheme 4 (a) *N*⁴-Benzoyl cytosine, HMDS, pyridine, SnCl₄, DCE, reflux, 28% (25% returned **12**), 1/1, α/β , then fractional precipitation, 10% for **21- α** , 6% for **21- β** . (b) From **21- α/β** , NH₃, MeOH, 40 °C, 96% crude, then preparative HPLC, 44% for **22- α** , 34% for **22- β** ; From **21- β** , NH₃, MeOH, 63% (c) *m*-CPBA, H₂O, MeCN, 15%, 4/1 d.r. at S.

respectively. ¹³C NMR analysis confirmed a significant downfield shift of C1' and C4' from δ_C 65.1 and 51.7 ppm in **16** to δ_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, α/β mixture, regardless of the anomeric ratio of the starting mesyl glycoside.^{10,26} In order to target 4'-thiogemcitabine, silylated *N*⁴-benzoyl cytosine was first glycosylated with donor **11**, using TMSOTf as activator. These conditions were unsuccessful (no product was isolated) and SnCl₄ 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*⁴-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- α** was confirmed through selective 1D NOESY, where through-space dipolar interactions between H₁ and H₃ were observed (Scheme 4 and ESI Fig. S5†). Anomer **22- β** 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 δ_C 59.7 and 46.3 ppm respectively in **22- β** to δ_C 84.6 and 72.8 ppm respectively in **23**.

2.4. Biological Evaluation

Nucleoside analogues **15**, **16**, **19**, **20**, **22- β** 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 ₅₀ (μM) U87-MG	CC ₅₀ (μM) PANC-1
1	Ara-C	0.19	0.43
2	Gemcitabine	0.01	0.21
3	19	0.59	12.0

and their CC₅₀ values compared to commercial arabinocytidine (Ara-C) and gemcitabine (Table 1). Only analogue **19** displayed measurable cytotoxicity, with a CC₅₀ value of 0.59 μM in U87-MG cells and 12 μM in PANC-1 cells (entry 3, Table 1); all other analogues had CC₅₀ values >200 μM. The data for **19** were not immediately comparable to Ara-C or gemcitabine, as both displayed superior CC₅₀ 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,²⁷ 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.

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