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NMR studies on 4-thio-5-furan- and 4-thio-5-thiophene-modified nucleosides

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1. Introduction

Nucleosides are the key molecules playing the fundamental roles in many biological processes, including cellular survival and growth. Modified nucleoside have been designed to understand and to elucidate these processes and consequently used as potential drugs because of their structural similarity to natural ones.\textsuperscript{1,2} We have been working on designing and developing 4-thiothymidines as effective anti-cancer agents in combination with UVA irradiation. Previously we reported 4-thiothymidine\textsuperscript{3,4} and its 5-bromo\textsuperscript{5} and 5-iodo-deoxyuridine\textsuperscript{6} as potential anti-tumor drugs.\textsuperscript{7,8,9} More recently we worked on such thio-analogues by conjugating 4-thiothymine with an aromatic ring, such as furan and thiophene, to shift their UVA absorption towards longer wavelengths to enhance the sensitivity to UVA irradiation.

In this paper, we report our findings from a systematic NMR study of these rarely available modified nucleosides using various NMR techniques (including COSY, NOESY) and also compare these findings with those acquired by using x-ray crystallography to offer a better understanding of the structural information of these modified nucleosides in solution and in solid state. Such structural knowledge would help to appreciate how these thio-analogues would work with UVA light and ultimately to design and produce modified nucleosides as anti-cancer therapeutics.

2. Results and Discussion

2.1. Synthesis and characterization

\textit{Chemical synthesis:} The target products, 4-thio-5-(furyl-2-yl/thiophen-2-yl)-pyrimidine deoxyribonucleosides (2a and 3a) and 4-thio-5-(furyl-2-yl/thiophen-2-yl)-pyrimidine ribonucleosides (2b and 3b) were prepared from their corresponding deoxy-uridine (1a) and uridine (1b) as shown in Scheme 1 (below). The preparation involved a 5-step synthesis (protecting the sugar hydroxyl groups; iodination at the 5-position of the base; replacing the iodo group with a ring (furan/thiophene); thiation at the 4-position of the base and finally releasing the sugar hydroxyls from the protecting groups). A detailed synthesis will be published in elsewhere.

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\end{itemize}
Characterization: The structures of 4-thio-5-(furyl-2-yl/thiophen-2-yl)-pyrimidine nucleosides (2a-b and 3a-b) have been thoroughly characterized and confirmed by various spectrometric studies, including FTIR and HR-MS.

2.2. NMR study of compounds 2 and 3.

2.2.1. \(^1\)H NMR

For the brevity of this paper, a modified nucleoside, 4-thio-5-thiophene-ribouridine (3b), is illustrated as a typical example. A section of 1D \(^1\)H-NMR spectrum of 3b is shown below. The protons on the nucleoside can be classed into three types: sugar, base and ring (furan/thiophene). In general chemical shifts for sugar protons are below 6 ppm, the protons form thiophene are located around 7ppm while the proton (6-H) of the base is above 8ppm. Their accurate assignments will be detailed accordingly.

(Figure 1 and its legend here)

a) Assignment of the sugar protons

The chemical shift of 1'-H has been well established and generally located at around 6 ppm. In the case of 4-thio-5-thiophene-ribouridine (3b), it is found to be at 5.76 ppm, from which we can readily locate its neighboring proton (i.e. 2'-H) via their cross peak (Peak A, in the Left panel of Figure 2). By following the arrow, the 2'-H would lead us to its cross peak (Peak B) with 2'-OH.

The carbon at 5'-position has two bonded protons which are the same chemically, but non-identical magnetically. As this set of protons is unique in the whole molecule and can be easily identified as the pair at the region below 4 ppm (more accurately at 3.56 and 3.72 ppm, see the right end of Figure 1 and the top right corner in the left panel of Figure 2). So we can start from here to trace its neighboring protons via peak C (crossing with 4'-H) and peak D (crossing with 5'-OH). The remaining signals for 3'-OH and 3'-H can be identified via their cross peak E. These assignments are further supported by the following lines of evidence: a) all three OH signals disappeared during D\(_2\)O exchange, b) the cross peaks between 2'-H and 3'-H and between 3'-H and 4'-H are identifiable in the range of 4 ppm.

(Figure 2 and its legend here)

The chemical shifts for the deoxy-sugar protons of 4-thio-5-thiophene-deoxyribouridine (3a) have an identical pattern except 2'-H has a much lower \(\delta\) value since its attached carbon-2 is not bonded directly to the electron-withdrawing O atom.
b) Assignment of the base protons (N3-H and 6-H)

There are only two protons on the base of the 5-substituted nucleosides (e.g. 2 and 3). (See Scheme 1 for the chemical structures). One is an imino proton (N3-H, at N3-position) and can be found at the far left end (lowest field) of the 1H NMR spectrum. The chemical shift of N3-H in 3b is found to be at 12.89 ppm and noticeably higher than those of the equivalent imino protons of un-thiolated thymine bases (usually between 11 and 12 ppm). This increased δ value can be ascribed to the presence of sulfur at the 4-position of the molecule (3b). The imino proton is exchangeable, so this type of NMR signal has been verified by D2O exchange. The other proton on the base is 6-H. As it is bonded with the carbon within the electron-rich and conjugated base, its chemical shift can be found at the relatively lower field (8.51 ppm). This assignment has been also confirmed by 2D (1H-13C) spectrum (data not shown).

c) Assignment of the protons in the 5-membered rings (thiophene and furan).

The chemical structure of C-5-linked thiophene is shown in the left panel of Figure 3. In the ring there are three protons, of which 4”-H is the only proton neighbored (thus closely coupled) with two protons (i.e. 3”-H and 5”-H). So the signal at 7 ppm, which has cross peaks with both 3” and 5”-protons, can be tentatively assigned as 4”-H (shown in the right panel of Figure 3). The signal located at 7.5 ppm is in the lowest field among these three protons and so can be putatively assigned as 5”-H, as it is close to the sulfur atom. From 5”-H, we can find its cross peak with 4”-H (F) and then track to 4”-H. From there, we can identify another cross peak (G), leading to the remaining proton (i.e. 3”-H). In addition 1H-13C COSY spectrum was also used to provide further supports to the assignment of these three ring protons (see the section of 13C NMR assignment below).

(Figure 3 and its legend here)

The chemical shifts for the proton at the furan ring of 4-thio-5-furan-ribouridine (2b) have a very similar pattern to those of the thiophene analogue (3b) except 5”-H has a higher δ value as the proton at 5”-position is close to the electron-withdrawing O atom in 2b. For the related deoxynucleoside analogues (2a and 3a), the NMR data on these 5-membered rings (furan and thiophene) are very similar, and all 1H NMR peaks for the target nucleosides (2 and 3) have been identified and the data are listed in Table 1.

(Table 1 here)

For comparison, Table 1 also includes 1H NMR data13,14 of 5-(furyl-2-yl)-deoxyribouridine (here named as 4a) and 5-(furyl-2-yl)-ribouridine (4b). Compounds 4a and 4b are the 4-oxy analogues to compounds 2a and 2b (i.e. 4-thio-5-(furyl-2-yl)-deoxyribouridine and 4-thio-5-(furyl-2-yl)-ribouridine. By comparison of the data of 4a/4b with those of 2a/2b, it is clear both assignments agree
very well. The only difference is on the N$_3$-H proton (see the highlighted values in Table 1). This is because 4a/4b have an oxygen atom at the 4-position while 2a/2b contain a sulfur atom at the same position. The presence of sulfur at the 4-position shifts its neighbouring N$_3$-H to a lower field (i.e. a higher $\delta$ value), consistent with our early observations.$^{11,12}$

2.2.2. $^{13}$C NMR

As $^{13}$C NMR would provide complimentary and additional structural information to $^1$H NMR, thus we also carried out a systemic study of these modified nucleosides. Our approach was first to generate a complete 1D $^{13}$C spectrum of one of our modified nucleosides and then assign each of the signals with the aid of other techniques. Again we use 4-thio-5-thiophene-ribouridine (3b) as an example. A complete 1D $^{13}$C spectrum (Fig. S1) is shown in electronic supplementary info (ESI). The assignments of these peaks are discussed individually in each of the three individual parts (sugar, base and the ring) as illustrated below.

a) Assignment of the sugar carbons

The above-described $^1$H-NMR data can be used as a starting point for assigning $^{13}$C NMR signals, thus it is feasible to trace their corresponding carbons from the identified protons. This was exampled by $^1$H-$^{13}$C 2D NMR of 3b. The sugar section is shown in Figure 4 (for the full spectrum, see Fig. S2 in ESI).

It is straightforward to find out from the section of $^1$H-$^{13}$C 2D NMR (Figure 4) that 1'-H has its corresponding $^{13}$C signal at near 90 ppm that is the signal for the carbon at 1'-position (ie. C-1'), see the dotted line in Figure 4. Similarly for other sugar protons (i.e. 2'-H, 3'-H, 4'-H and 5'-H), the chemical shifts of the related carbons can be clearly identified from Figure 4 and listed in Table 2. It is worth noting that the chemical shifts for C-1' carbons in the ribo-sugar (eg. 2b and 3b) are always higher than those of C-4' carbons while in the deoxyribose sugar (eg. 2a and 3a) the chemical shifts for C-1' are lower than those of C-4', see Table 2. This generality was also noted in our early work.$^{12}$ This can be ascribed to the fact the presence of oxygen atom at the 2'-position (of ribosugar) has a stronger effect on its directly neighbouring C-1’ carbon than its slightly distant C-4’ carbon.

(Figure 4 and its legend here)

b) Assignment of the base carbons

The pyrimidine base has four carbons (C-2, C4, C-5 and C-6), of which only C-6 has a bonded H atom. Thus the signal for C-6 can be readily identified from the known 6-H via $^1$H-$^{13}$C 2D NMR (HMQC technique). Taking 3b again as an example, as the peak of singlet ($\delta$ 8.51 ppm) has been previously assigned as 6-H (cf. Table 1), the 6-H peak can be traced in the HMQC spectrum to identify a cross-peak leading to its coupled carbon at 135.77ppm. (see Fig. S2 in ESI). However the other three carbons (C-2, C-4 and C-5) are all quaternary carbons (without bonded hydrogens).
Thus, HMQC is no use in this instance. HMBC (heteronuclear multiple bond correlation) is a possible means; the only non-exchangeable proton in the base is at the 6-position and is of three bond distance to both C-2 and C-4 and of two bond distance to C-5. So HMBC could be used to identify C-5 among them, but is unlikely to provide a conclusive solution to distinguish between 2-C and 4-C. Distortionless Enhancement by Polarization Transfer (DEPT) is a useful technique, which can allows us to determine multiplicity of carbon atoms substitution with hydrogens. As those carbon atoms without hydrogen attached, namely quaternary carbons, would become invisible in a DEPT spectrum. By comparing 1D $^{13}\text{C}$ NMR of 3b and its DEPT-135 (see Fig. S3a and S3b in ESI), it is easy to see that the peaks at 187 ppm (C-4), 147 ppm (C-2), 137 ppm (C-2") and 118 ppm (C-5) are missing in the DEPT-135 (Figure 5) and thus are identified as quaternary carbons. Three of them are from the base (i.e. C-2, C4 and C-5) and the other is from C-2” of the thiophene.

(Figure 5 and its Legend here)

In our early work\textsuperscript{12} we have demonstrated that presence of sulfur atom at the 4-position makes the chemical shift of C-4 move toward extremely low field, thus the peak with the highest $\delta$ value (187 ppm) should be assigned for C-4. C-2 is a type of urea and its $\delta$ value should be relatively higher, thus we can assign the peak at 147 ppm as C-2, and the peak at 118 ppm can be tentatively assigned for C-5 since its chemical shift is affected by the electronegativity of the substituent linked to C-5 position.\textsuperscript{12} The remaining quaternary carbon (137pp) can thus be tentatively assigned for C-2” of the thiophene, see below for further discussion.

3) Assignment of the ring (thiophene) carbons

The chemical structure of linked thiophene and its labelling are shown in Figure 6.

(Figure 6 and its legend here)

There are four carbon atoms (C-2”, C3”, C-4” and C-5”) in the ring of thiophene. As each of the three carbons (C-3”, C-4” and C-5”) has a bonded hydrogen, so they can be readily identified via $^1\text{H}$$^{13}\text{C}$ COSY spectrum (Figure 6). Although C-3” ($\delta=126.2$) and C-4” have a similar value ($\delta=126.2$) in $^{13}\text{C}$ NMR, however their respective values for $^1\text{H}$ NMR are noticeably different and thus can be assigned confidently. We have used the same approach to other target nucleosides and their $^{13}\text{C}$ data are listed in Table 2.

(Table 2 here)

Table 2 also includes $^{13}\text{C}$ NMR data\textsuperscript{13} of 4a [5-(furyl-2-yl)-deoxyribouridine] for comparison. The assignments of 4a are in good agreement with the assignments of 2a (its 4-thio-analogue). Again the sole difference is on the carbon at the 4-position, see the values in bold format. It is worth mentioning that $^{13}\text{C}$ data for 4b [5-(furyl-2yl)-uridine] has been listed, not assigned.\textsuperscript{14}
2.2.3. Relative orientation of the moieties

Nuclear Overhauser Effect spectroscopy (NOESY) is a useful tool to establish the correlations between nuclei that are spatially close and can provide valuable information about molecular structures. Thus, we used NOSEY technique to study the structural orientation among nucleoside’s moieties: the base, the ring and the sugar. Again take 3b as an example. Its NOESY spectrum is shown in Figure 7.

(Figure 7 and its legend here)

The cross peaks in NOESY indicate the concerned nuclei are spatially close. In this case, peak K suggest that the proton at 6”-position of the base (i.e. 6-H) is spatially close to 3”-H. Cross peaks L and M indicate 6-H is also spatially close to the protons at 2’-position (i.e 2’-H) and 3’-position (i.e. 3’-H) of the sugar. Therefore, we can propose the orientation of the thiophene is upward (parallel orientation), namely the sulfur atom is located at upper part of the ring as shown in Figure 7 insert. This model is consistent with our findings from x-ray structural studies shown at in Figure 8.

(Figure 8 and its legend here)

However the orientation for 5’-furan-analogue is quite different. We were able to observe NOE effects for 6-H of the base with 2’-H and 3’-H of the sugar, but no NOE effect was observed between 6-H and 3”-H (see Fig. S4 in ESI), implying the furan ring is downward (antiparallel orientation), namely the oxygen atom in the furan is away from the sulfur at the 4-position of the base. Again this finding is also consistent with our results from x-ray structural study of 4-thio-5’-(furan)-ribouridine (2b) shown in Figure 8.

It is comforting to see this same finding obtained by NMR (from a solution state) and by x-ray crystallography (from a solid state) on the orientation of the base relative to the ring (furan/thiophene). However, lacking is the suitable explanation of why 3b has a parallel orientation while 2b has an antiparallel structure. Although we could attribute these orientations to the facts that the large-sized sulfur atom in 3b has to avoid the stereo hindrance from the base and the sugar moieties, thus keeping its parallel orientation while the relatively smaller oxygen atom in 2b does not have the necessity to do so. More work will be required to completely answer these questions.

3. Conclusions

4-thio-5’-furan- and 5-thiophene-modified ribouridines and their 2’-deoxy analogues have been successfully prepared. In addition to standard analyses, their $^1$H and $^{13}$C NMR have been systemically investigated and various NMR spectroscopic approaches are used to unambiguously assign all protons and all carbons in these novel modified nucleosides. The orientations of the base (4-thiouridine or its deoxy analogue) relative to the ring (furan or thiophene) are confirmed by both NMR and x-ray crystallographic studies.
4. Experimental Section

General procedures for the synthesis of modified nucleosides (2 and 3)

Melting point was determined on a XR-4-type micro-melting point detector without correction. The compounds synthesized were purified by column chromatography using silica gel (200–300 mesh) except for recrystallization and thin-layer chromatography (TLC) using silica gel 60 F254 plates (250 mm; Qingdao Ocean Chemical Company, China). IR spectra were recorded using a Nicolet 550 Spectrophotometer (4000~400 cm⁻¹) with a crystalline sample spread on KBr pellets. UV spectra were recorded using UV-VIS spectrophotometer (JASCO, Japan); ¹H NMR and ¹³C NMR spectra were obtained by a 500 MHz Bruker AV-400 spectrometer with TMS as an internal standard. The mass spectrum was obtained on Hewlett-Packard 1100 LC/MSD spectrometer.

Protecting the sugar hydroxyl groups: The nucleoside (deoxyribouridine, 1a or uridine, 1b) (4.09 mmol) dissolved in anhydrous pyridine (12 mL), was treated with dry acetic anhydride (2.75 mL, 29 mmol) for 5 h. The yields were at 97-99%.

Iodination at the 5-position of the base: A mixture of acetyl protected nucleosides (0.5 mmol), iodine (76 mg, 0.3 mmol), Ceric ammonium nitrate (137 mg, 0.25 mmol) and MeCN (8 mL) was stirred at 80°C for 1 h. The yields were around 45%-70%.

Replacing the iodo group with a ring (furan/thiophene): Bis (triphenylphosphine) palladium (II) chloride (0.016 g, 0.023 mmol) and 2-(trimethyltannyl)-furan/thiophene (3.42 mmol) was added to the solution of 5-iodo-acetyl protected nucleosides (1.14 mmol). The mixture was heated at 90°C and refluxing for 3 h. The yields were around 75%.

Thioation at the 4-position of the base: 5-(furyl-2-yl/thiophen-2-yl)-acetyl protected nucleosides (2.32 mmol) were dissolved in peroxide-free 1,4-dioxane (50 mL) and P₂S₅ (1.0 g, 4.50 mmol) was added. The mixture was refluxed for 3-4 h. The yields were around 49-64%.

Releasing the sugar hydroxyls from the protecting groups: 4-thio-5-(furyl-2-yl/thiophen-2-yl)-acetyl protected nucleosides (2.14 mmol) were suspended in absolute MeOH (60 mL, 1.5 mmol) and saturated with dry ammonia gas. The mixture was stirred at room temperature for 4.5 h. The yields for the target products (4-thio-5-(furyl-2-yl/thiophen-2-yl) nucleosides (2a-b and 3a-b) were around 45%-70%.

NMR instruments and techniques

500 MHz from Bruker (AV-500, FT NMR) and 400 MHz from Bruker (AV-400, FT NMR) were used. The COSY spectra (DMSO-d₆) were obtained in the magnitude mode with 1024 points in the F2 dimension and 256 increments in the F1 dimension. Each increment FID was obtained with 12 scans with a relaxation delay of 2 s. HMQC spectra (DMSO-d₆) were obtained in the magnitude mode with 1024 points in the F2 dimension and 256 increments in the F1 dimension. Each increment FID was obtained with 16 scans with a relaxation delay of 2 s. NOESY spectra (DMSO-d₆) experiments were obtained in the magnitude mode with 2048 points in the F2
dimension and 256 increments in the F1 dimension. Each increment FID was obtained with 16 scans with a relaxation delay of 2 s.

5. Acknowledgements

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6. References

Table 1: $^1$H NMR data for all protons in furan- and thiophene-modified nucleosides

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*) Data$^{13}$ for 4a [5-(furyl-2yl)-2'-deoxyribouridine] and data$^{14}$ for 4b [5-(furyl-2yl)-ribouridine] are from the literature
Table 2 $^{13}$C NMR data for all carbons in furan- and thiophene-modified nucleosides

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*) The $^{13}$C data and assignments of 4a [5-(furyl-2yl)-2’-deoxyribouridine] is from literature $^{13}$. 
Scheme 1. Synthetic routes to 4-thio-5-(furyl-2-yl/thiophen-2-yl)-pyrimidine nucleosides. The conversional numberings are used for the sugar and base. The numberings of the ring (furan or thiophene) are shown in the top right of the structures 2 and 3.

\[
\begin{align*}
1a & : R=H \\
1b & : R=OH \\
2a & : R=H, X=O \\
2b & : R=OH, X=O \\
3a & : R=H, X=S \\
3b & : R=OH, X=S \\
\end{align*}
\]

i: Ac$_2$O/pyridine; ii: I$_2$, CAN/MeCN; iii: PdCl$_2$(PPh$_3$)$_2$; iv: P$_2$S$_5$; v: NH$_3$/CH$_3$OH
Figure 1. Section of $^1$H NMR spectrum of 4-thio-5-thiophene-ribouridine (3b) and its assignments.
Figure 2. Left: Section of 2D $^1$H-$^1$H NMR of 3b. Right: chemical structure and numberings for the sugar moiety of 3b. The cross peaks are labelled as A (between 1'-H and 2'-H), B (between 2'-H and 2'-OH), C (between 4'-H and 5'-H), D (between 5'-H and 5'-OH) and E (3'-H and 3'-OH).
Figure 3. Left: chemical structure and labeling for the C5-linked-thiophene moiety of 3b; Right: a section of 2D $^1$H-$^1$H NMR of 3b. The cross peaks are labelled as F (4"-H and 5"-H) and G (3"-H and 4"-H).
Figure 4 Left: Sugar section of $^1$H-$^{13}$C COSY spectrum of 4-thio-5-thiophene-ribouridine (3b). Right: Chemical structure and labelling of the sugar.
Figure 5. The signals of C-2 and C-5 (the base) and that of C-2" (the ring) disappeared in the DEPT-135 and the signal of C-4 (δ=187 ppm) is out of the scale. Left: Section of 1D $^{13}$C NMR of 3b (Upper) and its DEPT-135 (Lower); Right: Chemical structure and labelling of the base and 5-attached thiophene.
Figure 6. NMR signals of thiophene ring in $^1$H-$^13$C COSY spectrum of 4-thio-5-thiophene-ribouridine (3b).
Figure 7. NOESY spectrum of 4-thio-5-(thiophene)-ribouridine (3b). Cross peak K: between 6-H of the base and 3”-H of the ring, cross peak L: between 6-H of the base and 2’-H of the sugar, cross peak M: between 6-H of the base and 3’-H of the sugar.
Figure 8: Molecular structures and absolute configurations of 4-thio-5-(thiophene)-uridine (3b) and 4-thio-5-(furan)-uridine (2b) determined by x-ray crystallography. Full structural data are deposited at the Cambridge Crystallographic Data Centre, depository number: 1479957 and 1479956.