The synthesis, conformation and hydrolytic stability of an N,S-bridging thiophosphoramidate analogue of thymidylyl-3′,5′-thymidine†

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A 3′-N,5′-S-bridging thiophosphoramidate analogue of thymidylyl-3′,5′-thymidine was synthesised under aqueous conditions.1H NMR conformational measurements show that the 3′-N-substituted deoxyribose ring is biased towards the ‘north’, RNA-like conformation. Rate constants for hydrolysis of the analogue were measured at 90 °C in the pH range 1.3–10.9. The pH-log k_{obs} profile displays a pH-independent region between approximately pH 7 and 10 (t_{1/2} ~13 days). Under acidic conditions, k_{obs} displays a first order dependence on [H_{3}O^{+}].

A Introduction

Phosphate analogues, where oxygen atoms have been replaced by nitrogen or sulfur, are important mechanistic enzymology probes.1 These heteroatom substitutions serve to alter the electrophilicity at P, change leaving group properties, and the interactions between these atoms and metal ions at the active sites of enzymes and ribozymes. Sulfur substitutions, in particular, offer the ability to study cation binding through metal ion rescue experiments, and the use of phosphorothiolates has proven the existence of general acid–base catalysed cleavage of phosphodiester bonds in ribozymes.1–5 Oligonucleotides containing modified phosphate groups show increased resistance towards (ribo)nucleases and enhanced therapeutic effects.6–8 Modified phosphates also offer the potential for modulating the structural properties of nucleic acid assemblies such as the i-motif.9

Substitution of the O-heteroatoms of phosphoryl groups has also been used to facilitate phosphorylation and nucleic acid ligation technologies. To detect single nucleotide polymorphisms and facilitate signal amplification, Kool employed the nucleophilicity of sulfur anions to allow templated ligation through S-alkylation.8,10–17 We have exploited the nucleophilicity of amines to facilitate the efficient aqueous N-phosphorylation of amines,18–20 and N-thiophosphorylation plus S-alkylation of thiophosphoramidates.21–23 Amine nucleophilicity has also been harnessed to promote enzyme-free templated-ligation between 3′-amino-substituted oligonucleotides and 5′-activated phosphodiester nucleosides.24,25

We now demonstrate the application of aqueous N-thiophosphorylation plus S-alkylation towards the ligation of two nucleosides to afford thiophosphoramidate analogue TnpsT 1 of the dinucleotide, TpT 2 (Fig. 1). We study its conformational preference and hydrolytic stability across a broad pH range, with a view towards applying our aqueous strategies in nucleic acid ligations and bioconjugations.

† Electronic supplementary information (ESI) available: 1H, 13C and, where applicable, 31P NMR spectra of synthetic intermediates and analogue 1, HPLC calibration data, pH-Temperature corrections, further details of individual kinetics experiments, example chromatograms, and tabulated HPLC data. See DOI: 10.1039/c6ob01270a

Fig. 1 3′-Amino-3′-deoxythymidylyl-(3′→5′)-5′-deoxy-5′-thiothymidine (TnpsT 1) and its natural counterpart, thymidylyl-(3′→5′)-thymidine (TpT 2).

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B Synthesis

3′-Amino-3′-deoxythymidyl-(3′→5′)-5′-deoxy-5′-thiothymidine (TnpsT, 1) was chosen as a target because starting materials for our proposed synthetic route (Scheme 1) were readily accessible. The amine, 3′-amino-3′-deoxythymidine 3 was accessed as a hydrochloride salt via the reduction of 3′-azido-3′-deoxythymidine (AZT). 5′-Deoxy-5′-iodothymidine 5 was prepared by 5′-tosylation of thymidine, followed by conversion to the iodide using sodium iodide in acetone.

3′-Amino-3′-deoxythymidine 3 was N-thiophosphorylated using our pH-optimised protocol, where an aqueous solution of hydrochloride salt 3·HCl was maintained at pH 12 using KOH(aq) from an autotitrator during the addition of 1.0 equiv. of PSCl₃ dissolved in MeCN. This afforded crude thiophosphoramidate 4 (approximately 65% conversion by ³¹P NMR spectroscopy).

The alkylating agent, 5′-deoxy-5′-iodothymidine 5, showed poor solubility at neutral pH, however, deprotonation of the thymine base (pKₐ ~10) increased solubility markedly. Thus pH 12 was maintained throughout the addition of 5′-deoxy-5′-iodothymidine 5 to thiophosphoramidate 4. Under these conditions, 98% of the crude thiophosphoramidate 4 was converted to TnpsT 1 as determined by ³¹P NMR spectroscopy. TnpsT 1 was isolated by ion exchange chromatography in 64% yield (based on starting amine 3) as a triethylammonium salt, which was converted to the K⁺ salt for subsequent conformational and kinetic studies.

C Conformational analysis of TnpsT 1

Modified (deoxy)riboses display perturbed north/south conformational preferences (Fig. 2). Given our long-term intention to employ our synthetic approach in nucleic acid templated ligations, that would generate ligated products containing a thiophosphoramidate motif, we sought to gauge the conformational preference of TnpsT 1 using NMR methods.

The elucidation of solution-state ribose conformations by means of ¹H NMR J-coupling values was pioneered by Altona and Sundaralingam, and the effect on the conformation of thiophosphate-containing dinucleosides was investigated by Bevers et al. using similar methods. Rinkel and Altona found the sum of the J₁′–₂′ and J₁′–₂″ coupling constants, ΣH₁′, to be linearly correlated with the proportion of the south conformer through eqn (1), where Pₛ is the proportion of the ‘south’ conformer:

\[
Pₛ = \frac{\sum H₁′ - 9.8}{5.9}
\]

Many of the ¹H NMR signals of TnpsT 1 are coincident, and second-order couplings complicate the extraction of J values of the deoxyribose protons. The signals for both C₁′ protons, however, are well separated, and the J₁′–₂′ and J₁′–₂″ coupling values were 7.5 and 4.0 Hz, respectively for the 3′-amino-3′-deoxythymidine (Tnp) residue of 1. The C₁′–H signal at 6.28 ppm for the 5′-deoxy-5′-thiothymidine fragment (psT) pre-
D Kinetics and mechanism of TnpS hydrolysis

Hydrolysis experiments on TnpS 1 were carried out at 90 °C in buffered aqueous solutions with pHs ranging from 1.32 to 10.91, at intervals of approximately one pH unit (pH values calculated at 90 °C based on values measured at 25 °C, see ESI†). Aliquots of substrate 1 in each buffered solution were sealed into vials, and heated at 90 °C. Samples were removed from the heating bath or block at suitable intervals, the remaining starting material and products were resolved by HPLC, and the ratios of the integrals of the substrate and hydrolysis products relative to an internal standard were assessed.

At each pH, separate experiments were performed, using 10 and 100 mM buffer concentrations in order to check for buffer-promoted hydrolysis pathways. Acetate and formate buffered-experiments afforded rate constants that appeared to be dependent on buffer concentration. Thus, additional experiments were performed using 40 and 70 mM buffers, and kobs-buffer concentration plots were extrapolated to estimate the buffer-dependent and buffer-independent rate constants (see ESI†).

The log kobs-pH profile for the hydrolysis of TnpS 1 displayed a pH-independent ‘plateau’ from ~pH 7 to 10 with t½ ~13 days, while at pH 1.32 the half-life was nine seconds (red trace in Fig. 4). The rapidity of reaction at lower pH values put practical limits on our ability to further explore this region. At the high pH extreme, the appearance of insoluble materials in the reaction mixture suggested etching of the glass vials, which precluded the straightforward exploration of the higher pH extreme within the format of our experimental design.

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k_{\text{obs}} = \frac{k_H(10^{-pH}) + k_hK_{a1}}{10^{-pH} + K_{a1}}
\]  

(2)

Data for the disappearance of TnpS 1 were found to fit eqn (2), where rate coefficients \(k_0\) and \(k_H\) represent the contributions to \(k_{\text{obs}}\) of the neutral/zwitterionic forms \(1(\text{neutral})\) and monocationic form \(1H^+\) respectively (Scheme 2). The acid dissociation constant between \(1H^+\) and the kinetically indistinguishable neutral forms \(1(\text{neutral})\) is captured in \(K_{a1}\). A single data point at pH 10.91 suggests a potential downward trend in reactivity towards higher pHs. This may be associated with
nucleobase ionisation ($K_{a1}$) of 1(neutral), however, there are insufficient data to substantiate this hypothesis.

The reactivity on the pH plateau, with $k_0 = 6.3 \times 10^{-7} \text{ s}^{-1}$, is similar to the related analogues Tnp(s)T 6 and TnpT 7 that were studied by Ora et al. (blue and green traces in Fig. 4).32 The lack of an observed plateau in reactivity at lower pH values limits our ability to unequivocally assign values to the interdependent variables $k_H$ and $K_{a1}$. Based on the fitting of the available data, however, values of $k_H < 0.15 \text{ M}^{-1} \text{ s}^{-1}$ and $pK_{a1} < 1$ were estimated, which align with those observed for TnpT 7.

The similarity in reactivity profiles of TnpsT 1 and TnpT 7 suggests that mechanisms are likely to be similar. This is borne out in product analysis studies, and illustrative examples are discussed below (Scheme 3).

At pH 7.0 and 7.7 the largest detected peak by HPLC is thymine 8, derived from initial depyrimidinylation (route A) of either thymidine site within TnpsT 1 and subsequent fragmentation of the resulting species, as seen by Ora et al. for Tnp(s)T 6 and TnpT 7.32 Given the remoteness of the phosphoryl-sites from the C1' sites where de-pyrimidinynylations occur, it is unsurprising that the reactivities of TnpsT 1, Tnp(s)T 6 and TnpT 7 in the pH independent regions are similar. At pH 6, some depyrimidinylation is observed, however, P-N cleavage is now evident, with amine 3 being observed at a similar reten-

Scheme 3 Mechanistic pathways for the hydrolysis of TnpsT 1.
tion time to thymine 8 (routes A and B). Another product appears at a much longer retention time, with a lag in its formation. We believe this to be disulfide 11 formed from thiol 10 through oxidation, which is expected to be relatively facile at this pH, and has been reported in a similar system.33 We were, however, unable to confirm this by HPLC in a MS-compatible buffer system. Thiol 10 is formed by rapid dephosphorylation of phosphorothioate 9, which arises from acid promoted P–N scission. At pH 3.2, the product chromatograms are simpler, displaying only two major peaks. Amine 3 represents one of these peaks, derived from phosphorothioate 9 (route B). Thiol 10 is expected to be relatively stable towards oxidation under these conditions. The overlap of the pH-log $k_{\text{obs}}$ profiles of TnpsT 1 and TnpT 7 in the acidic region suggests that either the values of $k_{\text{th}}$ and $k_{\text{sh}}$ are identical for these species, or that ionisation and reactivity compensate each other to arrive at identical $k_{\text{obs}}$ values.

E Conclusions

TnpsT 1, which is an analogue of thymidyl-3′,5′-thymidine 2, was not successfully synthesised under aqueous conditions, without protecting groups. NMR-based analyses revealed a predominantly ‘north’, ‘RNA-like’ C3′-endo conformational preference for the 3′-aza-substituted deoxyribose (Tnp) fragment of TnpsT 1. Hydrolytic studies on TnpsT 1 yielded a near-identical profile to non-thio-analogue TnpT 7, where for pH > 7, dephosphorylation dominates, and P–N scission is dominant for lower pHs. The combination of simple aqueous synthesis, knowledge of conformational preference and stability of the linkage will allow us to exploit N,S-bridging nucleotide systems in future applications.

F Experimental

Synthesis

3′-Amino-3′-deoxythymidine 3, hydrochloride salt. Adapting a literature procedure,34 3′-azido-3′-deoxythymidine (1.00 g, 3.74 mmol) and triphenylphosphine (1.54 g, 5.87 mmol) were dissolved in pyridine (8 ml) and the mixture was stirred at room temperature for 1 h. Ammonia solution (30 ml, 35%) was then added, and the mixture was stirred overnight. The suspension was diluted with water (30 ml) and extracted with chloroform (3 × 30 ml) before being lyophilised. The solid residue was dissolved in ethanol (100 ml) and hydrogen chloride gas was bubbled through the solution until precipitation was observed. The precipitate was isolated by filtration, and washed with a small quantity of diethyl ether. Additional product was obtained by adding diethyl ether (500 ml) to the filtrate, collecting and washing the precipitate. The isolated solids were combined and dried under vacuum overnight yielding a total of 846 mg, 81%; mp 253–255 °C (decomp., from ethanol); $\nu_{\text{max}}$ cm$^{-1}$ 3392, 3032, 1694, 1644, 1470; $\delta_{\text{H}}$ (400 MHz, D$_2$O) 1.86 (3H, s, C5-CH$_3$), 2.54–2.70 (2H, m, C2′-H$_3$), 3.81 (1H, dd, J = 12.6, 4.6, C5′-H$_3$), 3.89 (1H, dd, J = 12.6, 3.4, C5′-H$_3$), 4.06 (1H, dt, J = 8.1, 5.5, C3′-H), 4.19–4.28 (1H, m, C4′-H), 6.28 (1H, t, J = 6.8, C1′-H), 7.62 (1H, d, J = 1.1, C6-H); $\delta_{\text{C}}$ (100 MHz, D$_2$O) 10.5, 33.8, 49.1, 59.7, 81.5, 84.1, 110.5, 136.6, 150.5, 165.4; $\mu$/242.1142 ( [M + H]$^+$, 100%), requires 242.1141, 264.0961 ([M + Na]$^+$, 90).

5′-Deoxy-3′-(4-tolueneformyl)thymidine. Adapting a literature procedure,26 thymidine (3.92 g, 16.2 mmol) was dissolved in pyridine (20 ml) in a round-bottomed flask, and placed in a water-ice bath. 4-Toluenesulfonyl chloride (3.83 g, 20.2 mmol), dissolved in pyridine (20 ml) was added dropwise over 10 min. Stirring was continued for a further 24 h. The solution was then poured into ice water (100 ml) and the mixture was extracted with ethyl acetate (2 × 60 ml). The organic extracts were washed with saturated sodium bicarbonate solution (40 ml), and water (40 ml) before being dried over MgSO$_4$. The solvents were then removed under reduced pressure, and the residue was recrystallised from water to give the tosylated nucleoside, 5′-deoxy-5′-(4-tolueneformyl)thymidine (1.57 g, 24%). $\delta_{\text{H}}$ (400 MHz, (CD$_3$)$_2$SO) 1.76 (3H, s, C5-CH$_3$), 2.02–2.09 (1H, m, C2′-H$_3$), 2.11–2.19 (1H, m, C2′-H$_3$), 2.41 (3H, s, CH$_3$-Ar) 3.83–3.88 (1H, m, C3′-H), 4.12–4.20 (2H, m, C4′-H and C5′-H$_3$), 4.25 (1H, dd, J = 7.2, 3.4, C5′-H$_3$), 5.04 (1H, d, J = 4.4, OH) 6.14 (1H, app. t, J = 7.2, C1′-H) 7.38 (1H, d, J = 1.8, C6-H) 7.47 (2H, d, J = 8.3, m-OSO$_2$Ph) 7.79 (2H, d, J = 8.3, o-OSO$_2$Ph) 11.33 (1H, s, NH) $\delta_{\text{C}}$ (400 MHz, (CD$_3$)$_2$SO) 12.1, 21.1, 38.3, 69.9, 70.1, 83.1, 84.0, 109.8, 127.6, 130.2, 132.1, 135.9, 145.1, 150.3, 163.6. 5′-Deoxy-3′-iodothymidine 5. 5′-Deoxy-5′-tosylthymidine (1.57 g, 3.96 mmol) and sodium iodide (2.97 g, 19.8 mmol) were placed in a round-bottomed flask and dissolved in the minimum volume of acetone. The solution was heated at reflux for 24 h, before the solvent was removed under reduced pressure. The residue was recrystallised from water to yield the product (1.20 g, 86%). $\delta_{\text{H}}$ (400 MHz, (CD$_3$)$_2$SO) 3.90 (3H, s, C5-CH$_3$), 5.20 (1H, d, J = 13.5, 6.2). $\delta_{\text{C}}$ (100 MHz, H, d, J = 13.5, 8.1, 6.2, C2′-H$_3$), 3.29 (1H, dd, J = 10.4, 6.3, C5′-H$_3$) 3.52 (1H, dd, J = 10.4, 6.3, C5′-H$_3$), 3.80 (1H, dt, J = 6.2, 2.8, C3′-H), 4.15–4.21 (1H, m, C4′-H), 5.49 (1H, d, J = 4.3, OH) 6.22 (1H, dd, J = 8.0, 6.2, C1′-H) 7.53 (1H, d, J = 1.5, C6-H) 11.35 (1H, s, NH).

3′-Amino-3′-deoxythymidylyl-(3′–5′)-5′-deoxy-5′-thiothymidine, triethylammonium salt 1-Et$_3$N$^+$H. First 3′-amino-3′-deoxythymidine-N-thiophosphoramidate 4 was prepared according to the previously reported phosphorylation procedure.22 3′-Amino-3′-deoxythymidine, hydrochloride salt 3-HCl (139 mg, 0.500 mmol) was dissolved in water and made up to 5 ml and pH 12 with water and potassium hydroxide solution (1 M). Thiophosphoryl chloride solution (1.50 ml, 0.333 M in MeCN) was added slowly using a Hamilton® microlitre syringe, with vigorous stirring, and with the tip of the syringe below the surface of the reaction mixture. Throughout the experiment, the pH was kept constant at pH 12 using a 1.00 M solution of potassium hydroxide, added by an autotitrator equipped with a pH probe. The experiment was considered to be complete when the autotitrator needed to add negligible volumes of pot-
assum hydroxide solution to the reaction mixture in order to maintain a constant pH. The lyophilised thio phosphoramidate was redissolved in water, and made up to 5 ml at pH 12 with water and potassium hydroxide solution (1 M). 5′-Deoxy-5′-iodothymidine 3 (352 mg, 1.00 mmol) was added to the solution with stirring, while the pH was maintained at 12 with potassium hydroxide solution (1 M) by an autotitrator. Once the 5′-deoxy-5′-iodothymidine 3 had fully dissolved and no further addition of potassium hydroxide was required to maintain the pH, the solution was sealed to prevent losses owing to evaporation and heated to 50 °C. At intervals, aliquots were removed from the reaction vessel and analysed by 31P NMR spectroscopy. The S-alkylation process was monitored based on the disappearance of the signal for thio phosphoramidate 4 at δ ~44 ppm, and the appearance of a signal for TnpST 1 at δ ~22 ppm. The reaction was continued until the unalkylated thio phosphoramidate starting material had been completely removed; the solution was then allowed to cool to room temperature. The pH of the reaction mixture was measured and found to be 10.45. The solution was lyophilised and redissolved in 1 M TEAB buffer, then purified by anion exchange chromatography with a flow rate of 5 ml min⁻¹ over a DEAE-Sepharose® resin. Triethylammonium bicarbonate buffer was applied in a 0 to 0.15 M gradient over 3 h. A second chromatographic purification using the same method was required to remove all impurities to yield 3′-amino-3′-deoxythymidylyl-(3′→5′)-5′-deoxy-5′-thiothymidine as its triethylammonium salt 1Et₂N+TH (212 mg, 64%). δ1 (700 MHz, D2O) 1.29 (9H, t, J 7.3, CH3(CH2)3), 1.88 (3H, d, J 1.2, A- or B-C5CH3), 1.89 (3H, d, J 1.2, A- or B-C5CH3), 2.36–2.45 (3H, m, A-C2H3 and B-C2H3), 2.49 (1H, ddd, J 14.0, 8.1, 3.9, A-C2H3), 3.04–3.11 (2H, m, C5′-CH3), 3.21 (6H, q, J 7.0, HN(CH2CH3)3), 3.78–3.85 (2H, m, A-C3′H and A-C5′H), 3.86–3.89 (1H, m, A-C5′H), 4.14–4.20 (2H, m, A- or B-C4′H), 4.46–4.49 (1H, m, B-C3′H), 6.16 (1H, dd, J 7.4, 4.0, A-C1′H), 6.25 (1H, app. t, J 6.7, B-C1′H), 7.67 (1H, d, J 1.2, A- or B-C6H), 7.71 (1H, d, J 1.2, A- or B-C6H); δc (151 MHz, D2O) 8.2 (HN(CH2CH3)3), 11.5 (A- and B-C5CH3), 32.0 (B-C5′), 38.0 (B-C2′), 38.5 (A-C5′), 46.6 (HN(CH2CH3)3), 58.9 (A-C3′), 60.2 (A-C5′), 72.0 (B-C3′), 84.5 (A-C1′), 84.7 (B-C1′), 84.9 (B-C4′), 85.5 (A-C4′), 111.1 (A- or B-C5), 111.3 (A- or B-C5), 137.4 (A- or B-C6), 137.5 (A- or B-C6), 151.4, 151.4, 166.1, 166.3, 171.1; δs (162 MHz, D2O) 21.6 (1P, app. q, J 9.7, HNPO3S); m/z 560.1207 [(M – HN+Et2)]⁻, 100%) requires 560.1216, 1121.2450 ([2M – 2K + H]⁺).

HPLC standard – potassium p-nitrobenzensulfonate

p-Nitrobenzenesulfonfyl chloride (222 mg, 1.00 mmol) was placed in a flask with potassium hydroxide solution (2 ml, 1.00 M) and water (20 ml). The solution was heated at reflux for 3 h before being lyophilised to yield a mixture of the desired product and potassium chloride in a 1 : 1 molar ratio. (231 mg, 98%) δ1 (400 MHz, D2O) 8.00 (2H, dt, J 8.9, 1H m- to sulfonate), 8.35 (2H, d, J 8.9, 1H o- to sulfonate); δc (101 MHz, D2O) 124.3, 126.9, 148.1, 149.1.

Hydrolysis studies

See ESI† for details of the hydrolysis studies.

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Notes and references