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A Metal-Mediated Base Pair with a [2+1] Coordination Environment

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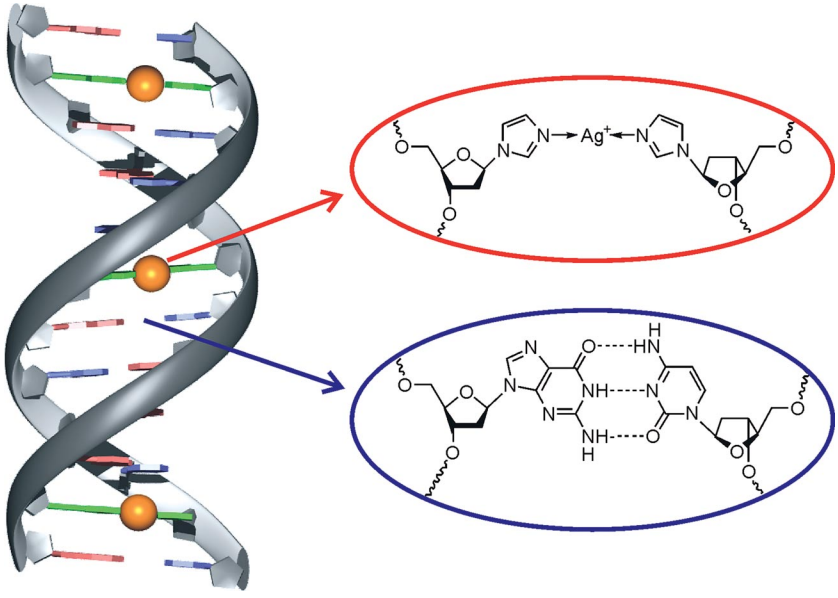
A silver(I)-mediated base pair based on azole-derived ligands only was devised. The base pair comprises the monodentate imidazole nucleoside and a nucleoside carrying the new bidentate ligand 4-[(1*H*-1,2,4-triazol-1-yl)methyl]-1*H*-1,2,3-triazole. The silver(I) ion is hence coordinated in a trigonal planar [2+1] environment. A representative DNA duplex comprising the new base pair is stabilized by 6 °C upon binding one equivalent of silver(I). CD spectroscopy was used to confirm that the duplex adopts the canonical B-type conformation. The base pair represents the first example of a metal-mediated base pair with a [2+1] coordination environment.

Introduction

Nucleic acids, and in particular DNA, have emerged as important supramolecular scaffolds for the three-dimensional arrangement of functional molecules.[1] While most of these functional molecules are based on purely organic moieties,[1b] the incorporation of metal complexes is gaining more and more attention.[1a] It is well known that metal ions are involved in almost every aspect of nucleic acid chemistry.[2] Nonetheless, a site-specific introduction of transition metal ions is not trivial. A particularly interesting concept is the introduction of transition metal ions into the center of a nucleic acid duplex by forming metal-mediated base pairs. In this artificial base pairing system, the hydrogen bonds between complementary nucleobases are formally replaced by coordinative bonds to metal ions (Scheme 1).[3]



Scheme 1. Representation of a DNA duplex with hydrogen-bond-mediated and artificial metal-mediated base pairs. Adapted with permission from ref.[3b] Copyright Wiley-VCH Verlag GmbH & Co. KGaA.

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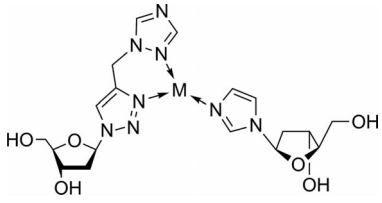
In most examples, the ligands involved in metal-mediated base pairs are artificial nucleobases. Nonetheless, several examples exist in which natural nucleobases such as thymine, cytosine, or uracil represent the basis of a metal-mediated

base pair.[4] The combination of metal-based functionality and self-assembling properties makes these metal–DNA conjugates attractive targets for chemists. Various applications are feasible,[3a] for example in sensing[5a–5d] or other uses based on the improved charge-transfer properties of DNA upon metalation.[5e,5f]

We have established various nucleic acid systems with metal-mediated base pairs derived from azole ligands,[6] including extensive studies with model nucleobases.[7] For example, the first structure determination of a nucleic acid with contiguous metal-mediated base pairs is based on imidazole–Ag^{I}–imidazole base pairs.[8] It was shown that neighboring base pairs of this type form in a cooperative manner.[9] Consequently, we set out to develop azole-based metal-mediated base pairs further. In particular, we aimed at devising a new base-pairing system with a trigonal planar coordination geometry of the central metal ion. This geometry should be achieved by combining one bidentate and one monodentate ligand. As the use of azole-based ligands had been very successful in the past, we devised the new bidentate ligand in a way to comprise two triazole moieties (tritri). Accordingly, the well-established imidazole nucleoside (imi) was planned to function as the monodentate ligand (Scheme 2). Alternatively, a pyrimidine nucleobase (cytosine, thymine) was considered as the monodentate ligand.



Scheme 2. Metal-mediated base pair with trigonal planar [2+1] coordination environment brought about by the ligands tritri and imi.

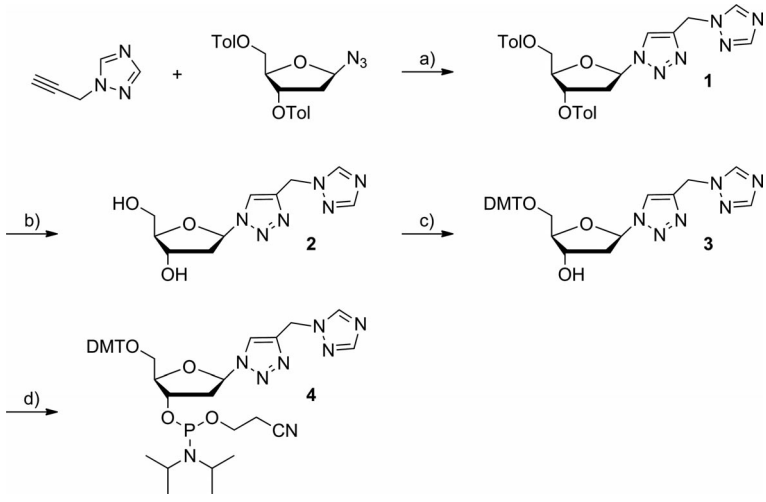
Results and Discussion

Scheme 3 shows the synthesis of the nucleoside carrying the new bidentate ligand tritri {4-[(1*H*-1,2,4-triazol-1-yl)-methyl]-1*H*-1,2,3-triazole}. Reaction of 1-propargyl-1*H*-1,2,4-triazole with a 2-deoxy-β-D-glycosyl azide gives the desired toluoyl-protected nucleoside **1**. After deprotection, free nucleoside **2** was converted to phosphoramidite **4** in a two-step synthesis. The phosphoramidite was used as a building block in automated solid-phase DNA synthesis. The oligonucleotide duplex under investigation is shown in Scheme 4. The same sequences – albeit with other artificial nucleobases – had been chosen in previous studies,[10] which enables a comparison with other metal-mediated base pairs.

5'-d(GAG GGA **X**AG AAA G)
3'-d(CTC CCT **Y**TC TTT C)

Scheme 4. Sequence of the oligonucleotide duplex under investigation (**X** = tritri, **Y** = imi, cytosine, or thymine).

To determine the melting temperature (T_m) of the oligonucleotide duplexes, temperature-dependent UV spectra were recorded. It is anticipated that the formation of a stable metal-mediated base pair leads to an increase in T_m due to the additional stabilization brought forward by the coordinative bonds. For reference purposes, related DNA sequences comprising canonical base pairs only had been investigated previously. The addition of Ag^{I} to these duplexes led to an increase in T_m of 2.5–3.5 °C, which was explained by nonspecific binding events due to an electrostatic interaction between the positively charged metal ion and the negatively charged DNA backbone.[10b] Hence, only ΔT_m values significantly larger than 3.5 °C can be considered as evidence for the formation of a stable metal-mediated base pair. Table 1 lists the increase in melting tempera-



Scheme 3. Synthesis of phosphoramidite **4**: a) THF/2-propanol/H_2O, $CuSO_4$, sodium ascorbate, 12 h, r.t. (Tol: *p*-toluoyl); b) MeOH, NH_3, 18 h, r.t.; c) dimethoxytrityl chloride (DMT-Cl), 4-(dimethylamino)pyridine (DMAP), pyridine, 3 h, r.t.; d) 2-cyanoethyl *N*,*N*-diisopropylchlorophosphoramidite (CEDIP-Cl), diisopropylethylamine (DIPEA), CH_2Cl_2, 30 min, r.t.

ture (ΔT_m) for the three DNA duplexes under investigation upon the addition of one equivalent of various transition metal ions.

Table 1. Melting temperatures of DNA duplexes comprising the bidentate ligand tritri (**X**) and a complementary imidazole, thymine, or cytosine (**Y**) in the presence of one equivalent of various transition metal ions.[a]

	Y = imidazole		**Y** = cytosine		**Y** = thymine	
M^{n+}	T_m /°C	ΔT_m /°C	T_m /°C	ΔT_m /°C	T_m /°C	ΔT_m /°C
–	21.7	–	21.6	–	23.0	–
Ag^{I}	27.7	+ 6.0	23.0	+ 1.4	25.0	+ 2.0
Au^{III}	21.8	+ 0.1	n.d.	n.d.	n.d.	n.d.
Cu^{II}	21.8	+ 0.1	22.2	+ 0.6	22.7	– 0.3
Co^{III}	21.6	– 0.1	n.d.	n.d.	n.d.	n.d.
Cr^{III}	21.6	– 0.1	n.d.	n.d.	n.d.	n.d.
Fe^{II}	21.6	– 0.1	n.d.	n.d.	n.d.	n.d.
Hg^{II}	21.7	±0.0	22.1	+ 0.5	23.1	+ 0.1
Mn^{II}	21.7	±0.0	n.d.	n.d.	n.d.	n.d.
Ni^{II}	21.8	+ 0.1	22.8	+ 1.2	23.3	+ 0.3
Zn^{II}	21.7	±0.0	n.d.	n.d.	n.d.	n.d.

[a] Conditions: 1 μM oligonucleotide duplex, 150 mM $NaClO_4$, 5 μM MOPS (pH 6.8), 1 μM metal salt. The estimated standard deviation of T_m amounts to 1 °C.

It can clearly be discerned that only one of the three possible combinations (tritri:imi, tritri:cytosine, tritri:thymine) is capable of forming a stable silver(I)-mediated base pair, namely tritri–Ag^{I}–imi, as evidenced by a ΔT_m of 6 °C. The melting curves of this duplex in the absence and in the presence of one equivalent of silver(I) are shown in Figure 1. None of the other transition metal ions under investigation had a significant effect on the melting temperature. The addition of the chelating ligand EDTA to the duplex does not lead to removal of the Ag^{I} from the metal-mediated base pair. As expected, silver(I) with its d^{10} electronic configuration seems to be the least selective metal ion in terms of preferred coordination geometry. This behavior has also become evident in other previously reported silver(I)-containing DNA systems such as the silver(I)-stabilized triple helix with a tricoordinate metal ion ([1+1+1] coordination)[11] or the silver(I)-mediated base pair proposed to possess a sixfold coordinated metal ion ([3+3] coordination).[12] Nonetheless, the tritri–Ag^{I}–imi base pair reported herein is the first example for a [2+1] coordination environment in a metal-mediated base pair.

Compared with other metal-mediated base pairs previously introduced into the same DNA sequence,[10] the tritri–Ag^{I}–imi base pair is the most stable one. The silver(I)-mediated base pair formed from dipicolylamine and imidazole (with a [3+1] coordination environment of the metal ion), the most stable one in a series of dipicolylamine–Ag^{I}–azole base pairs, stabilizes the duplex by 5.7 °C (and hence a bit less than tritri–Ag^{I}–imi).[10a] Moreover, homo base pairs of artificial nucleosides bearing a 6-(2′-thienyl)-purine or 6-(2′-furyl)-purine ligand incorporated into the DNA duplex shown in Scheme 4 did not seem to bind silver(I) at all.[10b] The increase in T_m upon the formation of the tritri–Ag^{I}–imi base pair is the same as that of the previously established imi–Ag^{I}–imi base pair (albeit in a different sequence context).[9] Hence, it can be estimated that the stability constant for the binding of Ag^{I} to a tritri:imi mispair has the same order of magnitude as that for an imi:imi mispair [$K = 3(1) \times 10^6$ M^{-1}].[9]

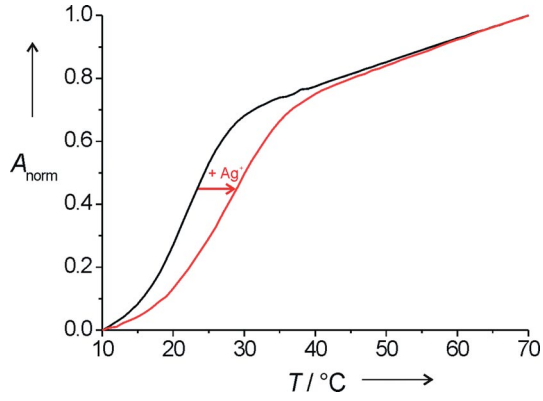


Figure 1. Melting curves of the DNA duplex comprising one tritri:imi base pair in the absence (black) and presence (red) of one equivalent of silver(I). The increase in melting temperature can clearly be discerned [$A_{norm} = (A - A_{min})/(A_{max} - A_{min})$ at 260 nm].

CD spectroscopy was applied to prove that the incorporation of the silver(I) ion into the DNA duplex does not induce any major conformational change. The CD spectra of the duplex in the absence and presence of one equivalent of silver(I) are shown in Figure 2. The two spectra overlap significantly. The CD spectra clearly demonstrate that the duplex adopts the canonical B-DNA conformation,[13] despite the presence of the artificial nucleobases. In fact, below 300 nm the CD spectra perfectly overlap with those of the same DNA sequence comprising a homo base pair of 6-(2′-furyl)-purine.[10b] Above 300 nm, the CD spectra of the DNA containing 6-(2′-furyl)-purine display additional Cotton effects due to the presence of the furyl moiety. The CD spectrum of the duplex with the tritri–Ag^{I}–imi base pair shows a slight deviation around 308 nm from the CD spectrum of the silver(I)-free duplex. It is tempting to speculate that this weak positive Cotton effect indicates a structural movement of the tritri ligand within the duplex to better accommodate the silver(I) ion. However, because of the weakness of the signal, no final conclusion can be drawn at this stage.

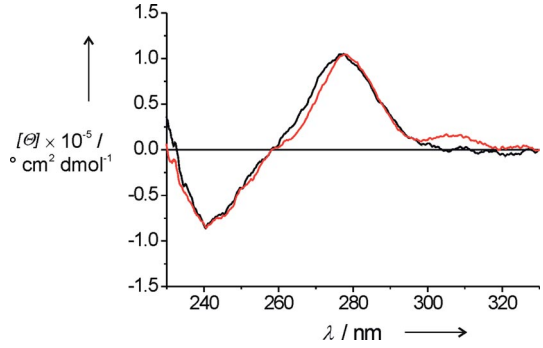


Figure 2. CD spectra of the DNA duplex comprising one tritri:imi base pair in the absence (black) and presence (red) of one equivalent of silver(I).

Conclusions

An artificial nucleoside that combines one 1,2,4-triazole entity with one 1,2,3-triazole moiety has been devised with the bidentate ligand tritri. This nucleoside forms a stable silver(I)-mediated base pair with a complementary imidazole nucleoside. The canonical pyrimidine nucleosides are not able to form metal-mediated base pairs with tritri. Moreover, silver(I) is the only transition metal ion that was found to stabilize the tritri:imi base pair. The resulting tritri–Ag^{I}–imi system represents the first metal-mediated base pair with a [2+1] coordination environment. A DNA duplex comprising such a base pair is stabilized by 6 °C with respect to the metal-free duplex. The only previous example for a silver(I) coordinated in a trigonal planar fashion inside DNA is a triple helix with a [1+1+1] coordination environment.[11] For that system, a stabilization of only 2 °C has been reported despite the use of excess silver(I). Hence, the tritri–Ag^{I}–imi base pair is significantly more stable than any previously reported DNA system with trigonally coordinated silver(I). By introducing the [2+1] coordination environment, the scope of metal-mediated base pairs is extended also towards tricoordinate metal ions.

Experimental Section

General: DNA syntheses were performed in the DMT-off mode with a K&A Laborgeräte H8 DNA/RNA synthesizer by following standard protocols according to a recently published procedure.[10b] The oligonucleotides were identified by MALDI-TOF mass spectrometry [purine-rich sequence: calcd. for $(M + H)^+$ 4118 Da, found 4121 Da; pyrimidine-rich sequence with **Y** = imi: calcd. for $(M + H)^+$ 3744 Da, found 3745 Da; pyrimidine-rich sequence with **Y** = C: calcd. for $(M + H)^+$ 3787 Da, found 3788 Da; pyrimidine-rich sequence with **Y** = T: calcd. for $(M + H)^+$ 3802 Da, found 3803 Da]. MALDI-TOF mass spectra were recorded with a Bruker Reflex IV instrument by using a 3-hydroxypicolinic acid/ammonium citrate matrix and applying a commercially available oligonucleotide with a molecular mass of 4577 Da as internal reference. NMR spectra were recorded with Bruker Avance(I) 400 and Bruker Avance(III) 400 spectrometers at 300 K. Chemical shifts were referenced to residual CD_3OH (CD_3OD, δ = 4.78 ppm) or TMS ($CDCl_3$, δ = 0 ppm). UV/Vis spectra were recorded with a Varian CARY BIO 100 spectrophotometer. CD spectra were recorded at 10 °C with a Jasco J-815 spectrometer. The CD spectra were smoothed, and a manual baseline correction was applied. 2-Deoxy-3,5-di-*O*-(*p*-toluoyl)-β-D-*erythro*-pentafuranosyl azide and 1-propargyl-1*H*-1,2,4-triazole were prepared according to literature procedures.[14]

Toluoyl-Protected tritri Nucleoside 1: To a mixture of 1-propargyl-1*H*-1,2,4-triazole (964 mg, 9.63 mmol) and 2-deoxy-3,5-di-*O*-(-*p*-toluoyl)-β-D-*erythro*-pentafuranosyl azide (3.17 g, 8.03 mmol) in THF/2-propanol (40 mL, 4:1) were added a solution of $CuSO_4 \cdot 5H_2O$ (402 mg, 1.61 mmol) in H_2O (8 mL) and sodium ascorbate (636 mg, 3.21 mmol). After stirring for 12 h at room temperature, the reaction was quenched by addition of EtOAc (150 mL). The organic layer was washed with aqueous EDTA solution (0.5%) until the aqueous layer was colorless. The organic phase was dried ($MgSO_4$). After filtration the solvent was removed. The crude product was purified by column chromatography, and **1** was obtained as a white solid (3.34 g, 6.65 mmol, 83%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.14 (s, 1 H, H5*), 7.93 [d, 2 H, H_{meta}(Tol)], 7.90 (s, 1 H, H3*), 7.84 [d, 2 H, H_{meta}(Tol)], 7.82 (s, 1 H, H5), 7.24 [m, 4 H, H_{ortho}(Tol)], 6.45 (t, 1 H, H1′), 5.75 (d, 1 H, H3′), 5.39 (m, 2 H, CH_2), 4.65 (q, 1 H, H4′), 4.61 (dd, 2 H, H5′, H5′′), 3.19 (dt, 1 H, H2′ or H2′′), 2.86 (ddd, 1 H, H2′ or H2′′), 2.43 [s, 3 H, CH_3(Tol)], 2.41 [s, 3 H, CH_3(Tol)] ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 166.1 (C=O), 164.9 (C=O), 152.2 (C3*), 144.6 (Tol), 144.2 (Tol), 143.3 (C4), 142.1 (C5*), 129.8 (Tol), 129.7 (Tol), 129.3 (Tol), 126.6 (Tol), 126.3 (Tol), 122.0 (C5), 118.9 (C5), 89.1 (C1′), 83.9 (C4′), 74.7 (C3′), 63.9 (C5′), 44.8 (*C*H_2), 38.3 (C2′), 21.7 [CH_3(Tol)] ppm. $C_{26}H_{26}N_6O_5$ (502.52): calcd. C 62.14, H 5.20, N 16.72; found C 62.17, H 5.21, N 16.47. HRMS: calcd. for $[M + Na]^+$ 525.1862; found 525.1858.

Free Nucleoside 2: Compound **1** (3.34 g, 6.64 mmol) was dissolved in a mixture of methanol (100 mL) and aqueous NH_3 (50 mL). After stirring overnight at room temperature the solvent was evaporated, and the crude solid was purified by column chromatography to obtain the desired product **2** as a white solid (1.68 g; 6.29 mmol, 95%). ^{1}H NMR (400 MHz, CD_3OD): δ = 8.59 (s, 1 H, H5*), 8.29 (s, 1 H, H3*), 8.01 (s, 1 H, H5), 6.44 (t, 1 H, H1′), 5.60 (s, 2 H, CH_2), 4.56 (q, 1 H, H3′), 4.05 (q, 1 H, H4′), 3.74 (dd, 1 H, H5′ or H5′′), 3.65 (dd, 1 H, H5′ or H5′′), 2.79 (m, 1 H, H2′ or H2′′), 2.54 (m, 1 H, H2′ or H2′′) ppm. ^{13}C NMR (100 MHz, CD_3OD): δ = 152.5 (C3*), 145.1 (C5*), 130.5 (C4), 124.1 (C5), 90.3 (C1′), 89.7 (C4′), 72.1 (C3′), 63.1 (C5′), 45.4 (CH_2), 41.7 (C2′) ppm. $C_{10}H_{14}N_6O_3$ (266.26) for **2**·0.25H_2O: calcd. C 44.34, H 5.40, N 31.05; found C 44.10, H 5.19, N 30.84. HRMS: calcd. for $[M + Na]^+$ 289.1025; found 289.1016.

DMT-protected tritri Nucleoside 3: Compound **2** (1.67 g, 6.29 mmol) was co-evaporated thrice with dry pyridine (20 mL) and then dissolved in dry pyridine (50 mL). To this reaction mixture were added catalytic amounts of DMAP under an argon atmosphere, followed by the addition of DMT-Cl (2.94 g, 7.55 mmol). The mixture was stirred for 3 h at room temperature. The solution was diluted with CH_2Cl_2 (100 mL) and washed with water (3 × 20 mL). The organic phase was dried (Na_2SO_4), and the solvents were evaporated to dryness. The crude product was purified with column chromatography to obtain **3** as a white foam (3.14 g, 5.53 mmol, 88%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.03 (s, 1 H, H5), 7.84 (d, 2 H, H3*, H5*), 7.33 (m, 2 H, DMT), 7.25–7.19 (m, 7 H, DMT), 6.79 (d, 2 H, DMT), 6.32 (t, 1 H, H1′), 5.27 (d, 2 H, CH_2), 4.63 (m, 1 H, H3′), 4.13 (m, 1 H, H4′), 3.77 (s, 6 H, O-CH_3), 3.31 (m, 2 H, H5′, H5′′), 2.80 (m, 1 H, H2′ or H2′′), 2.53 (m, 1 H, H2′ or H2′′) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 158.5 (DMT), 151.6 (C3*), 144.4 (C5*), 143.0 (DMT), 141.4 (C4), 135.5 (DMT), 135.4 (DMT), 130.0 (DMT), 129.3 (DMT), 128.4 (DMT), 128.1 (DMT), 127.8 (DMT), 126.9 (DMT), 121.9 (C5), 113.1 (DMT), 88.8 (C1′), 86.6 (C4′), 70.8 (C3′), 63.2 (C5′), 55.2 (OCH_3), 44.6 (CH_2), 40.8 (C2′) ppm. HRMS: calcd. for $[M + Na]^+$ 591.2332; found 591.2334.

Orthogonally Protected tritri Nucleoside 4: Compound **3** (724 mg, 1.27 mmol) was dissolved in freshly distilled CH_2Cl_2 (35 mL). To this solution were added DIPEA (650 µL, 3.82 mmol) and CEDIP-Cl (568 µL, 2.55 mmol) under an argon atmosphere. After 30 min of stirring at room temperature the mixture was diluted with EtOAc (75 mL). The organic phase was washed with saturated aqueous $NaHCO_3$ solution (30 mL) and dried ($MgSO_4$). The solution was concentrated to dryness. Column chromatography gave **4** as a yellowish oil (887 mg, 1.15 mmol, 90%). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.96 (s, 1 H, H5), 7.79 (s, 2 H, H5*, H3*), 7.27 (m, 2 H, DMT), 7.20–7.12 (m, 8 H, DMT), 6.72 (m, 2 H, DMT), 6.28 (t, 1 H, H1′), 5.22 (m, 2 H, CH_2), 4.67 (m, 1 H, H3′), 4.16 (m, 1

H, H4′), 3.79–3.63 [m, 8 H, OCH_3, $CH(CH_3)_2$], 3.49 (m, 2 H, CH_2CN), 3.23 (m, 2 H, H5′, H5′′), 2.78 (m, 1 H, H2′ or H2′′), 2.61 (m, 1 H, H2′ or H2′′), 2.53 (t, 2 H, OCH_2), 1.10–1.00 [m, 12 H, $CH(CH_3)_2$] ppm. ^{31}P {H} NMR (162 MHz, $CDCl_3$): δ = 149.4, 149.1 ppm. HRMS: calcd. for $[M + Na]^+$ 791.3410; found 791.3405.

Acknowledgments

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[1] a) T. J. Bandy, A. Brewer, J. R. Burns, G. Marth, T. Nguyen, E. Stulz, *Chem. Soc. Rev.* **2011**, *40*, 138–148; b) R. Varghese, H.-A. Wagenknecht, *Chem. Commun.* **2009**, 2615–2624.
[2] J. Müller, *Metallomics* **2010**, *2*, 318–327.
[3] a) P. Scharf, J. Müller, *ChemPlusChem* **2013**, *78*, 20–34; b) J. Müller, *Eur. J. Inorg. Chem.* **2008**, 3749–3763; c) Y. Takezawa, M. Shionoya, *Acc. Chem. Res.* **2012**, *45*, 2066–2076; d) G. H. Clever, M. Shionoya, *Coord. Chem. Rev.* **2010**, *254*, 2391–2402; e) G. H. Clever, C. Kaul, T. Carell, *Angew. Chem.* **2007**, *119*, 6340–6350; *Angew. Chem. Int. Ed.* **2007**, *46*, 6226–6236.
[4] a) D. A. Megger, N. Megger, J. Müller, *Met. Ions Life Sci.* **2012**, *10*, 295–317; b) S. Johannsen, S. Paulus, N. Düpre, J. Müller, R. K. O. Sigel, *J. Inorg. Biochem.* **2008**, *102*, 1141–1151; c) D. A. Megger, C. Fonseca Guerra, F. M. Bickelhaupt, J. Müller, *J. Inorg. Biochem.* **2011**, *105*, 1398–1404; d) A. Ono, H. Torigoe, Y. Tanaka, I. Okamoto, *Chem. Soc. Rev.* **2011**, *40*, 5855–5866.
[5] a) D.-L. Ma, H.-Z. He, K.-H. Leung, H.-J. Zhong, D. S.-H. Chan, C.-H. Leung, *Chem. Soc. Rev.* **2013**, *42*, 3427–3440; b) H.-Z. He, D. S.-H. Chan, C.-H. Leung, D.-L. Ma, *Nucleic Acids Res.* **2013**, *41*, 4345–4359; c) B. Y.-W. Man, D. S.-H. Chan, H. Yang, S.-W. Ang, F. Yang, S.-C. Yan, C.-M. Ho, P. Wu, C.-M. Che, C.-H. Leung, D.-L. Ma, *Chem. Commun.* **2010**, *46*, 8534–8536; d) D. S.-H. Chan, H.-M. Lee, C.-M. Che, C.-H. Leung, D.-L. Ma, *Chem. Commun.* **2009**, 7479–7481; e) T. Ehrenschwender, W. Schmucker, C. Wellner, T. Augenstein, P. Carl, J. Harmer, F. Breher, H.-A. Wagenknecht, *Chem. Eur. J.* **2013**, *19*, 12547–12552; f) S. Liu, G. H. Clever, Y. Takezawa, M. Kaneko, K. Tanaka, X. Guo, M. Shionoya, *Angew. Chem.* **2011**, *123*, 9048; *Angew. Chem. Int. Ed.* **2011**, *50*, 8886–8890.
[6] a) J. Müller, D. Böhme, P. Lax, M. Morell Cerdà, M. Roitzsch, *Chem. Eur. J.* **2005**, *11*, 6246–6253; b) D. Böhme, N. Düpre, D. A. Megger, J. Müller, *Inorg. Chem.* **2007**, *46*, 10114–10119.
[7] D. A. Megger, J. Kösters, A. Hepp, J. Müller, *Eur. J. Inorg. Chem.* **2010**, 4859–4864.
[8] a) S. Kumbhar, S. Johannsen, R. K. O. Sigel, M. P. Waller, J. Müller, *J. Inorg. Biochem.* **2013**, *127*, 203–210; b) S. Johannsen, N. Megger, D. Böhme, R. K. O. Sigel, J. Müller, *Nat. Chem.* **2010**, *2*, 229–234.
[9] K. Petrovec, B. J. Ravoo, J. Müller, *Chem. Commun.* **2012**, *48*, 11844–11846.
[10] a) K. Seubert, C. Fonseca Guerra, F. M. Bickelhaupt, J. Müller, *Chem. Commun.* **2011**, *47*, 11041–11043; b) I. Sinha, J. Kösters, A. Hepp, J. Müller, *Dalton Trans.* **2013**, *42*, 16080–16089.
[11] K. Tanaka, Y. Yamada, M. Shionoya, *J. Am. Chem. Soc.* **2002**, *124*, 8802–8803.
[12] N. Zimmermann, E. Meggers, P. G. Schultz, *J. Am. Chem. Soc.* **2002**, *124*, 13684–13685.
[13] D. M. Gray, R. L. Ratliff, M. R. Vaughan, *Methods Enzymol.* **1992**, *211*, 389–406.
[14] a) A. Štimac, J. Kobe, *Carbohydr. Res.* **2000**, *329*, 317–314; b) Y. Gao, H. Gao, C. Piekarski, J. M. Shreeve, *Eur. J. Inorg. Chem.* **2007**, 4965–4972.

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