Crystal Structures * of Cadmium(II) Complexes with Uridine 5′-Monophosphate (5′-UMP), $[Cd(5'\text{-}UMP)(H_2O)_2]\cdot 2H_2O$, and with 2′-Deoxyuridine 5′-Monophosphate (5′-dUMP), $[Cd_2(5'\text{-}dUMP)_2(H_2O)_6]$: † Phosphate-only Metal Bonding

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The crystal structures of the cadmium(II) complexes with uridine 5′-monophosphate (5′-UMP), $[Cd(5'\text{-}UMP)(H_2O)_2]\cdot 2H_2O$(1), and with 2′-deoxyuridine 5′-monophosphate (5′-dUMP), $[Cd_2(5'\text{-}dUMP)_2(H_2O)_6]$ (2), have been determined by *X*-ray analysis. Complex (1) crystallizes in space group *C*2 with a = 28.835(7), b = 14.241(4), c = 4.928(3) Å, β = 91.37(1)°, and Z = 4; complex (2) crystallizes in space group $P\bar{1}$ with a = 18.278(6), b = 7.572(3), c = 5.356(1) Å, α = 89.76(3), β = 98.22(2), γ = 93.74(3)°, and Z = 1. Both structures have been solved by heavy-atom methods and refined to R = 0.079 for (1) and 0.060 for (2), using 1 236 and 2 530 diffractometer data respectively. Both compounds are one-dimensional polymers of compositions $[\{Cd_2(5'\text{-}UMP)_2(H_2O)_4\}_n]$ for (1) and $[\{Cd_2(5'\text{-}dUMP)_2(H_2O)_6\}_n]$ for (2). The conformation of UMP and dUMP is *anti* about the glycosyl link, *gauche–gauche* about the C(4′)–C(5′) bond (except for one of the dUMP molecules which is *gauche–trans*), and the sugar puckers are *endo*-C(3′)/*exo*-C(2′) for UMP but *endo*-C(1′) and *exo*-C(4′) in dUMP. UMP or dUMP nucleotides are bonded to metal ions through their phosphate groups only and form columns of metal–phosphate clusters from which sugar–base moieties project outwards. These findings suggest that the helical structure of polyuridylic acid is probably destabilized by Cd^{II} due to interactions with phosphate groups and *not via* base co-ordination, as generally assumed.

In recent years, a great deal of interest has been attracted by metal-ion interactions with nucleic acids.[1] This is mainly because metal ions are involved in several nucleic acid processes, and in environmental effects, and certain metal complexes are useful as drugs or probes in structural investigations of nucleic acids.

However, in the growing body of structurally elucidated transition-metal ion–nucleotide complexes,[2] there have been only a few reports of metal complexes of uridine nucleotides, $[Co(5'\text{-}UMP)(H_2O)_5]\cdot 5H_2O$ [3] (5′-UMP = uridine 5′-monophosphate), $[\{Cu(5'\text{-}UMP)(dpa)(H_2O)\}_2]\cdot 5H_2O$ [4] (dpa = di-2-pyridylamine), and $[Cd(5'\text{-}UMP)(dpa)(H_2O)]\cdot H_2O$,[5] and no example of a complex of thymidine nucleotide, clearly due to difficulties of obtaining crystals suitable for *X*-ray study. We report here the preparation and the crystal structures of the cadmium(II) complexes of 5′-UMP (I) and 5′-dUMP [2′-deoxyuridine 5′-monophosphate, (II)], in which metal ions are bound solely to the phosphate groups of UMP or dUMP nucleotides to form columns of metal–phosphate clusters. The latter complex serves as a model for metal interactions with thymidine 5′-monophosphate [5′-TMP, (III)], where the C(5) site of the uracil base is substituted by a methyl group. The former complex is isostructural to the cobalt(II) analogue.[3]

Experimental

Preparation of Complexes.—An aqueous solution (0.1 mmol) of $Na_2(5'\text{-}UMP)$ or $Na_2(5'\text{-}dUMP)$ was added to a solution (0.1 mmol) of $Cd(NO_3)_2\cdot 4H_2O$ at room temperature. The solution (pH *ca.* 6) was stirred and set aside. Colourless crystals appeared after *ca.* 3 weeks, which were filtered off, washed with water, and air-dried.

Crystal Structure Analyses.—Unit-cell determination and refinement, and data collection followed normal procedures.[6] The crystal data and a summary of data collection and structure refinement are given in Table 1. A Rigaku diffractometer was employed in the ω–2θ scan mode. No corrections for absorption were applied because of the irregular shape of the crystal for $[Cd(5'\text{-}UMP)(H_2O)_2]\cdot 2H_2O$ (1) and because of the low μr value (linear absorption coefficient × thickness of crystal) for $[Cd_2(5'\text{-}dUMP)_2(H_2O)_6]$ (2).

Both structures were solved by heavy-atom methods and refined by block-diagonal least squares with anisotropic thermal parameters for all the non-hydrogen atoms. In these refinements, the function $\Sigma w(F_o - |F_c|)^2$ was minimized, applying a weighting scheme of the type suggested by Hughes.[7] This scheme gave satisfactory analyses of variance, $\Sigma w(F_o - |F_c|)^2$ *versus* F_o and $(\sin\theta)/\lambda$. No attempts were made to locate the hydrogen atoms. Scattering factors and anomalous dispersion factors were taken from ref. 8. Computations were carried out with the UNICS III program system,[9] on a FACOM M380 computer. The final atomic co-ordinates are given in Tables 2 and 3 for complexes (1) and (2), respectively.

Results

Interatomic distances and angles are listed in Tables 4 and 5. Close contacts involving hydrogen bonds are in Tables 6

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* *Supplementary data available* (No. SUP. 23896, 25 pp.): structure factors, thermal parameters, least-squares planes. See Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1984, Issue 1, pp. xvii—xix.

† The abbreviations used are those recommended by the IUPAC–IUB Commission on Biochemical Nomenclature, *Eur. J. Biochem.*, 1970, **15**, pp. 203—208.

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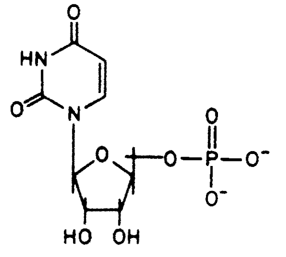
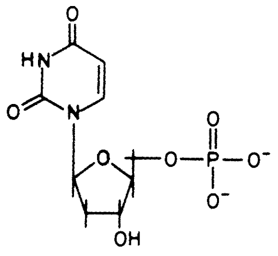
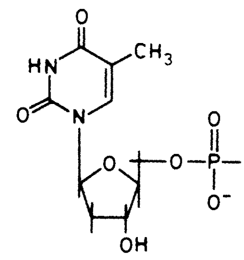


(I)



(II)



(III)

Table 1. Crystal data and summary of data collection and structure determination

Compound	$[Cd(5'\text{-}UMP)(H_2O)_2]\cdot 2H_2O$ (1)	$[Cd_2(5'\text{-}dUMP)_2(H_2O)_6]$ (2)
Molecular formula	$C_9H_{19}CdN_2O_{13}P$	$C_{18}H_{34}Cd_2N_4O_{22}P_2$
M	506.63	945.22
Crystal size/mm	0.05 × 0.05 × 0.12	0.025 × 0.09 × 0.40
Space group	$C2$	$P1$
a/Å	28.835(7)	18.278(6)
b/Å	14.241(4)	7.572(3)
c/Å	4.928(3)	5.356(1)
α/°		89.76(3)
β/°	91.37(1)	98.22(2)
γ/°		93.74(3)
U/Å^3	2 023.1	732.0
Z	4	1
D_c/g cm^{-3}	1.66	2.14
F(000)	1 016	472
Radiation (λ/Å)	Cu-K_α (1.5418)	Mo-K_α (0.710 69)
μ/cm^{-1}	105.2	18.1
2θ upper limit/°	130	55
No. reflections measured	2 021	2 868
No. unique observed reflections [$F_o > 3\sigma(F_o)$]	1 236	2 530
Weighting scheme, w	$w = 1.0$ for $F_o \leqslant 60.0$ $w^{\frac{1}{2}} = 60.0/F_o$ for $F_o > 60.0$	$w = 1.0$ for $F_o \leqslant 40.0$ $w^{\frac{1}{2}} = 40.0/F_o$ for $F_o > 40.0$
R	0.079	0.060
R'	0.108	0.077
No. variables	245	434

and 7, and Table 8 gives conformational parameters of the nucleotide molecules.

$[Cd(5'\text{-}UMP)(H_2O)_2]\cdot 2H_2O$ (1).—Complex (1) forms a one-dimensional polymeric structure of composition $[\{Cd_2(5'\text{-}UMP)_2(H_2O)_4\}_n]$ as shown in Figure 1 and in the schematic representation in Figure 2. Pairs of cadmium atoms [Cd(1) ··· Cd(2) pair 3.249(3) Å apart], which lie on a two-fold axis along *b* but which are crystallographically independent, are bound to four nucleotide molecules through their phosphate groups only [mean Cd–O, 2.29 Å], and to four water molecules [mean Cd–OH_2, 2.29 Å], with each metal atom being in a slightly distorted octahedral co-ordination arrangement. In turn, each phosphate group links two dinuclear units [Cd(1) ··· $Cd(1^{I})$ = Cd(2) ··· $Cd(2^{I})$, 4.928 Å ≡ cell dimension *c*], using all the phosphate oxygen atoms; oxygen O(6) bridges one Cd(1)–Cd(2) pair and two oxygens O(7) and O(8) cap the other *c*-translation related pair. An interesting structural feature is the formation of a cage-like clustering unit, [–Cd(1)/Cd(2)–phosphate–Cd(1)/Cd(2)–phosphate–], with a crystallographic two-fold axis parallel to the Cd(1)–Cd(2) pair (*b* axis) passing through the centre of this cage. The repetition of this cluster unit along *c* produces an infinite one-dimensional column of metal–phosphate clusters, from which the sugar–base portions of the nucleotides project to both sides in an antiparallel fashion. The uracil base is in the common *anti* [10] conformation with $\chi_{CN} = -172°$.[10] The ribose ring adopts a twist form with an *endo*-C(3′)/*exo*-C(2′) [10] pucker [displacement of C(3′) from the best place defined by O(1′), C(1′), C(2′), and C(4′) is 0.52 Å and that of C(2′) from the best plane defined by the remaining four atoms is 0.62 Å]. The conformation about the C(4′)–C(5′) bond is the commonly observed *gauche–gauche* [10] (Table 8). The crystal packing, as shown in Figure 3, is largely dominated by hydrogen-bonding interactions involving two water of crystallization molecules, uracil base atoms, and ribose hydroxyl groups; there are two hydrogen bonds which interconnect nucleotide molecules, between the base and the ribose hydroxyl groups [N(3) ··· O(3′) 2.79(3) and O(4) ··· O(2′) 2.72(3) Å]. There exists neither inter-base hydrogen bonding nor base–base stacking interactions, but instead, base–sugar O(1′) atom interactions are prominent (Table 6).

$[Cd_2(5'\text{-}dUMP)_2(H_2O)_6]$ (2).—Figure 4 shows a segment of the one-dimensional polymeric structure of (2) of composition $[\{Cd_2(5'\text{-}dUMP)_2(H_2O)_6\}_n]$ [see also schematic representation of structure (2) in Figure 2], where there are two crystallographically independent $Cd(5'\text{-}dUMP)(H_2O)_3$ units. Here again, nucleotide molecules bind to the metal ions through the phosphate groups only and form columns composed of metal–phosphate clusters similar to those found in complex (1)

Table 2. Atomic co-ordinates (× 10^4) for $[Cd(5'\text{-UMP})(H_2O)_2]\cdot 2H_2O$ (1) with estimated standard deviations in parentheses

Atom	*x*	*y*	*z*
Cd(1)	0*	4 782(2)	9*
Cd(2)	0*	2 500*	0*
P	632(2)	3 613(11)	4 947(9)
O(5′)	1 186(6)	3 561(28)	5 487(30)
O(6)	414(5)	3 598(25)	7 813(28)
O(7)	552(6)	4 473(13)	3 357(30)
O(8)	520(5)	2 680(14)	3 470(30)
C(5′)	1 421(8)	4 032(19)	7 570(41)
C(4′)	1 940(8)	3 892(17)	7 066(40)
C(3′)	2 091(9)	4 146(24)	4 199(47)
C(2′)	2 543(8)	3 595(39)	3 959(44)
C(1′)	2 402(9)	2 637(25)	5 406(50)
O(1′)	2 082(6)	2 938(14)	7 461(29)
O(2′)	2 915(6)	3 978(14)	5 487(36)
O(3′)	2 614(6)	5 066(14)	3 714(34)
N(1)	2 176(8)	1 948(17)	3 592(42)
C(2)	2 461(9)	1 510(19)	1 756(48)
O(2)	2 877(7)	1 703(17)	1 687(35)
N(3)	2 248(8)	857(19)	76(52)
C(4)	1 799(12)	639(30)	58(71)
O(4)	1 651(8)	13(20)	−1 657(39)
C(5)	1 502(12)	1 171(28)	1 810(69)
C(6)	1 702(12)	1 773(24)	3 574(48)
O(W1)	397(10)	5 892(21)	−2 466(52)
O(W2)	345(11)	1 397(17)	−2 566(53)
O(W3)	1 298(9)	5 766(20)	2 782(57)
O(W4)	1 139(17)	6 970(47)	8 053(97)

* Parameter fixed by symmetry.

Table 3. Atomic co-ordinates (× 10^4) for $[Cd_2(5'\text{-dUMP})_2(H_2O)_6]$ (2) with estimated standard deviations in parentheses

Atom	*x*	*y*	*z*
Cd(1)	0*	0*	0*
Cd(2)	−1 405(1)	−3 122(2)	−2 829(3)
P(1)	−1 662(2)	−198(6)	2 065(8)
P(2)	258(2)	−2 905(6)	−4 874(8)
N(11)	−4 531(8)	−1 949(19)	−840(25)
C(12)	−5 147(10)	−3 054(25)	−1 460(38)
N(13)	−5 230(9)	−4 482(20)	160(33)
C(14)	−4 749(10)	−4 723(21)	2 389(31)
C(15)	−4 135(10)	−3 499(22)	2 939(31)
C(16)	−4 055(10)	−2 151(23)	1 371(33)
O(12)	−5 544(7)	−2 894(18)	−3 394(22)
O(14)	−4 867(8)	−6 037(17)	3 668(26)
C(11′)	−4 398(10)	−289(30)	−2 411(39)
C(12′)	−4 435(13)	1 411(25)	−982(46)
C(13′)	−3 697(10)	2 436(19)	−1 095(30)
C(14′)	−3 307(9)	1 293(20)	−2 704(28)
O(11′)	−3 687(5)	−467(14)	−3 125(21)
O(13′)	−3 796(7)	4 174(17)	−2 093(33)
C(15′)	−2 543(11)	1 133(25)	−1 604(34)
O(15′)	−2 456(7)	63(18)	497(24)
O(16)	−1 178(7)	−853(17)	43(22)
O(17)	−1 833(8)	−1 536(22)	4 040(25)
O(18)	−1 317(7)	1 611(19)	3 048(28)
N(21)	3 159(8)	−1 124(18)	3 192(30)
C(22)	3 798(9)	−26(25)	3 001(32)
N(23)	3 900(8)	1 412(19)	4 628(28)
C(24)	3 475(11)	1 737(23)	6 530(35)
C(25)	2 860(11)	495(31)	6 616(34)
C(26)	2 704(13)	−896(34)	4 890(44)
O(22)	4 244(8)	−270(21)	1 636(27)
O(24)	3 601(10)	3 051(20)	7 884(28)
C(21′)	3 023(10)	−2 670(22)	1 491(36)
C(22′)	2 998(12)	−4 454(26)	2 960(38)
C(23′)	2 259(13)	−5 317(24)	1 908(38)
C(24′)	2 035(11)	−4 329(30)	−534(45)
O(21′)	2 262(10)	−2 634(21)	−51(29)
O(23′)	2 353(19)	−7 157(23)	1 323(54)
C(25′)	1 117(11)	−4 275(30)	−1 018(38)
O(25′)	1 075(7)	−3 229(18)	−3 321(24)
O(26)	−194(6)	−2 127(17)	−3 103(21)
O(27)	472(8)	−1 557(19)	−6 749(24)
O(28)	−34(11)	−4 641(23)	−6 022(37)
O(W11)	−353(12)	2 211(23)	−2 766(30)
O(W12)	596(8)	2 278(20)	2 981(27)
O(W13)	1 177(10)	564(20)	−1 467(44)
O(W21)	−984(8)	−5 265(16)	−122(24)
O(W22)	−1 936(8)	−5 419(18)	−5 558(28)
O(W23)	−2 528(8)	−3 553(23)	−1 220(31)

* Parameter fixed by symmetry.

[mean Cd–O (phosphate) distance is 2.24 Å and mean Cd–OH_2 distance is 2.35 Å]. The repeating cluster unit, [–Cd(1)/Cd(2)–phosphate–Cd(1)/Cd(2)–phosphate–], has a pseudo centre of symmetry at its centre. The main difference in the clustering mode between the two compounds is that in (2) the phosphate oxygen O(8) is not involved in co-ordination to Cd and is instead replaced by an apically positioned water molecule, O(W1). This water ligand forms a hydrogen bond with O(8) (broken lines in Figure 4) [O(18) ··· O(W11) 2.67(2) and O(28) ··· O(W21) 2.62(2) Å]. Due to these intra-columnar hydrogen bonds, the clustering unit is somewhat wider [Cd(1) ··· Cd(2) pair 3.550(1) Å apart] and longer [Cd(1) ··· Cd(1^{I}) = Cd(2) ··· Cd(2^{I}), 5.356 Å ≡ *c*] than that of complex (1). The nucleotide sugar–base moieties also project outwards to both sides, but in a parallel mode in this case. The two independent 5′-dUMP molecules show the common *anti* conformation about the glycosyl bonds with $\chi_{CN} = -125°$ for dUMP(1) and −124° for dUMP(2). However, the two deoxyribose rings exhibit rare puckers: *endo*-O(1′) for dUMP(1) [displacement of O(1′) from the best plane defined by the remaining four atoms is 0.22 Å] and *exo*-C(4′) for dUMP(2) [displacement of C(4′) from the best plane of the four atoms is 0.56 Å]. Orientations about the C(4′)–C(5′) bonds are the usual *gauche–gauche* for dUMP(1) and the rare *gauche–trans* form for dUMP(2). The crystal lattice is stabilized by inter-base hydrogen bonds formed between the ring nitrogen N(3) and the exocyclic carbonyl oxygen O(4) [N(13) ··· O(24) 2.88(2) and N(23) ··· O(14) 2.97(2) Å], by sugar–base hydrogen bonds [O(13′) ··· O(14) 2.78(2) and O(23′) ··· O(24) 3.13(4) Å], and by inter-columnar hydrogen bonds between ligation-free phosphate oxygen O(8) and water ligands [O(W21) ··· O(18) 2.99(2), O(W22) ··· O(18) 2.74(2), O(W11) ··· O(28) 3.02(3), and O(W12) ··· O(28) 2.76(2) Å] and between water ligands [O(W11) ··· O(W21) 2.79(2) Å] (Figure 5). Neither base–base stacking nor base–sugar O(1′) interactions are observed.

Comparison between the Structures of Complexes (1) *and* (2).—Obvious similarities are (*i*) ' phosphate only ' metal bonding with an octahedral metal co-ordination sphere and (*ii*) formation of metal–phosphate double chains with a cage-like repeating unit, $[–Cd–Cd–phosphate–Cd–Cd–phosphate–]_n$. Major differences involve (*i*) the composition of the polymeric unit, *i.e.* $[\{Cd_2(5'\text{-UMP})_2(H_2O)_4\}_n]$ for (1) where each Cd atom is attached to four oxygen atoms from four different phosphate groups and to two water molecules (all phosphate oxygens of a nucleotide molecule are involved in metal co-ordination), and $[\{Cd_2(5'\text{-dUMP})_2(H_2O)_6\}_n]$ for (2) where each Cd atom is bonded to three oxygens from three different phos-

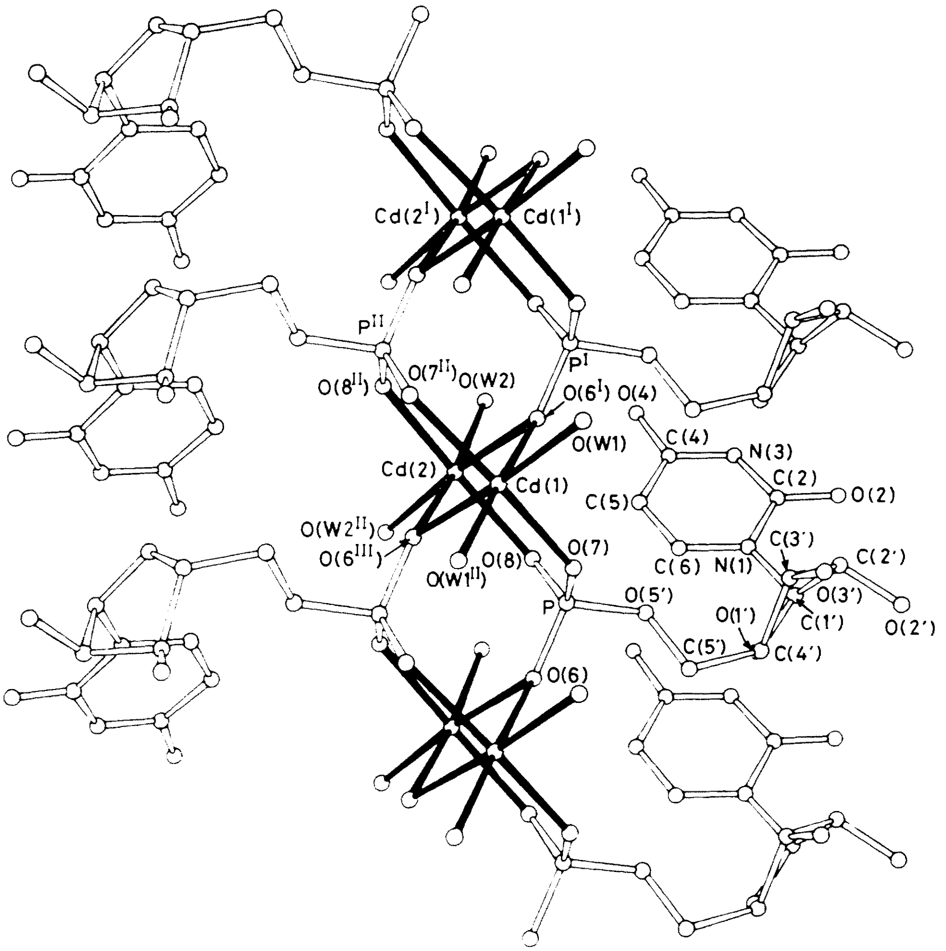
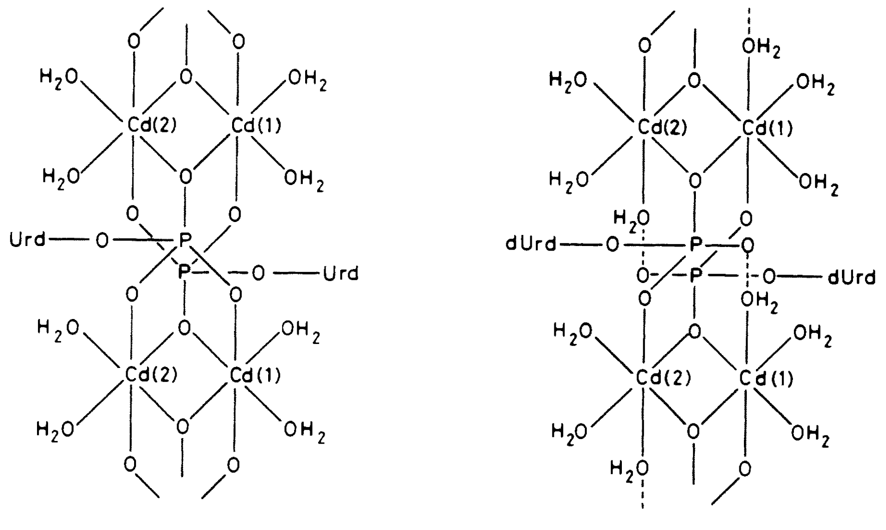


Figure 1. A segment of the polymeric [$\{Cd_2(5'\text{-}UMP)_2(H_2O)_4\}_n$] structure, showing the formation of a column of metal-phosphate clusters from which the sugar-base moieties project outwards in an antiparallel fashion. The UMP molecule exhibits an *endo*-C(3')/*exo*-C(2') sugar puckering. Note the interactions between the uracil bases and the sugar O(1') atoms of adjacent molecules. Covalent and co-ordinative bonds are respectively drawn in open and filled types (also in Figures 3—5). Roman superscripts indicate the following symmetry equivalent positions: I $x, y, z - 1$; II $-x, y, -z$; III $-x, y, 1 - z$



Complex (1) Complex (2)

Figure 2. A schematic representation of the structures of [$Cd(5'\text{-}UMP)(H_2O)_2$]·$2H_2O$ (1) and [$Cd_2(5'\text{-}dUMP)_2(H_2O)_6$] (2) (Urd = uridine, dUrd = 2'-deoxyuridine). Note the similarity in the arrangement of the cage-like clustering units consisting of two Cd atoms and two phosphates

Table 4. Interatomic distances (Å) and angles (°) with estimated standard deviations in parentheses for [Cd(5′-UMP)$(H_2O)_2$]·$2H_2O$ (1)

(*a*) Co-ordination sphere *

Cd(1)–O(6$^{\text{I}}$)	2.34(3)	Cd(2)–O(6$^{\text{I}}$)	2.26(3)
Cd(1)–O(7)	2.31(2)	Cd(2)–O(8)	2.26(1)
Cd(1)–O(W1)	2.31(3)	Cd(2)–O(W2)	2.26(1)
Cd(1) · · · Cd(2)	3.249(3)		
Cd(1)–O(6$^{\text{I}}$)–Cd(2)	89.9(5)		
O(6$^{\text{I}}$)–Cd(1)–O(6$^{\text{III}}$)	88.0(9)	O(6$^{\text{I}}$)–Cd(2)–O(6$^{\text{III}}$)	92.3(10)
O(6$^{\text{I}}$)–Cd(1)–O(7)	81.0(6)	O(6$^{\text{I}}$)–Cd(2)–O(8)	84.8(6)
O(6$^{\text{I}}$)–Cd(1)–O(7$^{\text{II}}$)	83.3(6)	O(6$^{\text{I}}$)–Cd(2)–O(8$^{\text{II}}$)	86.2(6)
O(6$^{\text{I}}$)–Cd(1)–O(W1)	89.2(10)	O(6$^{\text{I}}$)–Cd(2)–O(W2)	88.3(10)
O(6$^{\text{I}}$)–Cd(1)–O(W1$^{\text{II}}$)	175.7(8)	O(6$^{\text{I}}$)–Cd(2)–O(W2$^{\text{II}}$)	173.2(8)
O(7)–Cd(1)–O(7$^{\text{II}}$)	158.0(7)	O(8)–Cd(2)–O(8$^{\text{II}}$)	167.0(7)
O(7)–Cd(1)–O(W1)	99.5(8)	O(8)–Cd(2)–O(W2)	102.1(9)
O(7)–Cd(1)–O(W1$^{\text{II}}$)	95.4(8)	O(8)–Cd(2)–O(W2$^{\text{II}}$)	87.0(8)
O(W1)–Cd(1)–O(W1$^{\text{II}}$)	93.8(10)	O(W2)–Cd(2)–O(W2$^{\text{II}}$)	92.0(10)
Cd(1)–O(6$^{\text{I}}$)–P$^{\text{I}}$	128.9(18)	Cd(2)–O(6$^{\text{I}}$)–P$^{\text{I}}$	132.2(19)
Cd(1)–O(7)–P	129.7(11)	Cd(2)–O(8)–P	125.5(11)

(*b*) UMP ligand

N(1)–C(2)	1.39(3)	C(3′)–C(4′)	1.53(3)
C(2)–N(3)	1.38(4)	C(4′)–O(1′)	1.43(3)
N(3)–C(4)	1.33(4)	O(1′)–C(1′)	1.45(3)
C(4)–C(5)	1.45(5)	C(2′)–O(2′)	1.40(3)
C(5)–C(6)	1.34(5)	C(3′)–O(3′)	1.35(4)
C(6)–N(1)	1.39(4)	C(4′)–C(5′)	1.53(3)
C(2)–O(2)	1.23(3)	C(5′)–O(5′)	1.39(3)
C(4)–O(4)	1.29(5)	O(5′)–P	1.62(2)
N(1)–C(1′)	1.47(4)	P–O(6)	1.56(2)
C(1′)–C(2′)	1.60(6)	P–O(7)	1.47(2)
C(2′)–C(3′)	1.53(5)	P–O(8)	1.55(2)
N(1)–C(2)–N(3)	116(2)	C(4′)–O(1′)–C(1′)	112(2)
C(2)–N(3)–C(4)	125(3)	O(1′)–C(1′)–C(2′)	103(3)
N(3)–C(4)–C(5)	118(3)	C(1′)–C(2′)–O(2′)	107(2)
C(4)–C(5)–C(6)	118(3)	C(3′)–C(2′)–O(2′)	114(3)
C(5)–C(6)–N(1)	122(3)	C(2′)–C(3′)–O(3′)	110(3)
C(6)–N(1)–C(2)	121(2)	C(4′)–C(3′)–O(3′)	116(2)
N(1)–C(2)–O(2)	121(2)	C(3′)–C(4′)–C(5′)	115(2)
N(3)–C(2)–O(2)	124(2)	O(1′)–C(4′)–C(5′)	112(2)
N(3)–C(4)–O(4)	118(3)	C(4′)–C(5′)–O(5′)	106(2)
C(5)–C(4)–O(4)	124(3)	C(5′)–O(5′)–P	124(2)
C(2)–N(1)–C(1′)	116(2)	O(5′)–P–O(6)	105.6(8)
C(6)–N(1)–C(1′)	123(2)	O(5′)–P–O(7)	105.6(15)
N(1)–C(1′)–C(2′)	114(2)	O(5′)–P–O(8)	103.5(16)
N(1)–C(1′)–O(1′)	110(2)	O(6)–P–O(7)	115.6(16)
C(1′)–C(2′)–C(3′)	100(2)	O(6)–P–O(8)	109.3(15)
C(2′)–C(3′)–C(4′)	102(2)	O(7)–P–O(8)	115.9(9)
C(3′)–C(4′)–O(1′)	105(2)		

* Labelled atoms are identical with those in Figure 1.

phate groups and to three water molecules (one phosphate oxygen is not involved in metal ligation and forms an intracolumnar hydrogen bond with an axially bound water molecule). (*ii*) Another difference is the conformations of the nucleotide molecules, *i.e.* common sugar puckering at *endo*-C(3′)/*exo*-C(2′) in (1) and rare *endo*-O(1′) and *exo*-C(4′) in (2), and usual *gauche-gauche* conformations about C(4′)–C(5′) in (1) and (2) and a rare *gauche-trans* form in (2); these conformational varieties are probably due to differences in substitution at C(2′), hydroxyl for 5′-UMP and hydrogen for 5′-dUMP, which influence molecular interactions such as hydrogen bonding and van der Waals contacts. (*iii*) There are base–sugar O(1′) interactions, but neither inter-base hydrogen bonding nor base–base stacking in (1) and inter-base hydrogen bonding but neither base–base stacking nor base–sugar O(1′) interactions in (2).

Discussion

The present analysis confirms a suggestion [3] based on *X*-ray powder diffraction patterns that 5′-UMP reacts with Cd ions to form a compound similar to [Co(5′-UMP)$(H_2O)_2$]·$5H_2O$.[3] Therefore, the crystal structures of the *X*-ray characterized binary 5′-UMP complexes of Cd, Co,[3] and Mn[3] (*X*-ray powder diffraction studies) are essentially identical.

There is very little difference in the co-ordination behaviour towards transition-metal ions between the ribo- and deoxyribo-nucleotides UMP and dUMP. This tendency has also been observed in ribo- and deoxyribo-nucleotides of guanine [11] and cytosine [12] and is apparently due to the weak ligating power of the functional groups of sugars and bases.

It is of interest to compare the metal-binding modes for various nucleotides. For the purine series comprising adenosine, guanosine, and inosine nucleotides, ' base N(7) only '

Table 5. Interatomic distances (Å) and angles (°) with estimated standard deviations in parentheses for [Cd_2(5′-dUMP)$_2$(H_2O)$_6$] (2)

(*a*) Co-ordination sphere *

Cd(1)–O(16)	2.21(1)	Cd(2)–O(16)	2.29(1)
Cd(1)–O(26)	2.29(1)	Cd(2)–O(26)	2.32(1)
Cd(1)–O(27^{II})	2.20(1)	Cd(2)–O(17^{I})	2.14(1)
Cd(1)–O(W11)	2.29(2)	Cd(2)–O(W21)	2.27(1)
Cd(1)–O(W12)	2.45(1)	Cd(2)–O(W22)	2.35(1)
Cd(1)–O(W13)	2.41(2)	Cd(2)–O(W23)	2.34(1)
Cd(1) · · · Cd(2)	3.550(1)		
Cd(1)–O(16)–Cd(2)	104.2(5)	Cd(1)–O(26)–Cd(2)	100.7(5)
Cd(1)–O(16)–P(1)	124.1(7)	Cd(2)–O(16)–P(1)	130.8(7)
Cd(1)–O(26)–P(2)	136.1(7)	Cd(2)–O(26)–P(2)	123.1(7)
Cd(1)–O(27^{II})–P(2^{II})	141.9(9)	Cd(2)–O(17^{I})–P(1^{I})	146.9(9)
O(16)–Cd(1)–O(26)	78.4(4)	O(16)–Cd(2)–O(26)	76.5(5)
O(16)–Cd(1)–O(27^{II})	97.8(5)	O(16)–Cd(2)–O(17^{I})	96.0(5)
O(16)–Cd(1)–O(W11)	89.7(6)	O(16)–Cd(2)–O(W21)	95.9(4)
O(16)–Cd(1)–O(W12)	119.4(5)	O(16)–Cd(2)–O(W22)	165.9(5)
O(16)–Cd(1)–O(W13)	160.8(6)	O(16)–Cd(2)–O(W23)	84.0(5)
O(26)–Cd(1)–O(27^{II})	100.8(5)	O(26)–Cd(2)–O(17^{I})	92.4(5)
O(26)–Cd(1)–O(W11)	92.9(5)	O(26)–Cd(2)–O(W21)	89.7(5)
O(26)–Cd(1)–O(W12)	162.2(5)	O(26)–Cd(2)–O(W22)	117.5(5)
O(26)–Cd(1)–O(W13)	84.1(5)	O(26)–Cd(2)–O(W23)	159.6(5)
O(27^{II})–Cd(1)–O(W11)	165.5(6)	O(17^{I})–Cd(2)–O(W21)	168.0(5)
O(27^{II})–Cd(1)–O(W12)	77.0(5)	O(17^{I})–Cd(2)–O(W22)	81.8(5)
O(27^{II})–Cd(1)–O(W13)	93.3(6)	O(17^{I})–Cd(2)–O(W23)	95.4(6)
O(W11)–Cd(1)–O(W12)	88.5(5)	O(W21)–Cd(2)–O(W22)	86.8(5)
O(W11)–Cd(1)–O(W13)	83.2(7)	O(W21)–Cd(2)–O(W23)	86.5(6)
O(W12)–Cd(1)–O(W13)	78.4(6)	O(W22)–Cd(2)–O(W23)	82.3(6)

(*b*) dUMP ligands

	dUMP(1)	dUMP(2)		dUMP(1)	dUMP(2)
N(1)–C(2)	1.36(2)	1.40(2)	C(6)–N(1)–C(2)	122(2)	124(2)
C(2)–N(3)	1.40(3)	1.38(2)	N(1)–C(2)–O(2)	121(2)	126(2)
N(3)–C(4)	1.40(2)	1.40(3)	N(3)–C(2)–O(2)	123(2)	120(2)
C(4)–C(5)	1.41(2)	1.42(3)	N(3)–C(4)–O(4)	118(2)	122(2)
C(5)–C(6)	1.33(2)	1.39(3)	C(5)–C(4)–O(4)	124(2)	124(2)
C(6)–N(1)	1.38(2)	1.34(3)	C(2)–N(1)–C(1′)	121(1)	117(2)
C(2)–O(2)	1.19(2)	1.19(2)	C(6)–N(1)–C(1′)	117(1)	119(2)
C(4)–O(4)	1.23(2)	1.22(2)	N(1)–C(1′)–C(2′)	113(2)	112(2)
N(1)–C(1′)	1.53(3)	1.47(2)	N(1)–C(1′)–O(1′)	104(2)	110(1)
C(1′)–C(2′)	1.51(3)	1.56(3)	C(1′)–C(2′)–C(3′)	105(2)	103(2)
C(2′)–C(3′)	1.52(3)	1.50(3)	C(2′)–C(3′)–C(4′)	104(1)	104(2)
C(3′)–C(4′)	1.50(2)	1.52(3)	C(3′)–C(4′)–O(1′)	112(1)	106(2)
C(4′)–O(1′)	1.47(2)	1.34(3)	C(4′)–O(1′)–C(1′)	105(1)	106(2)
O(1′)–C(1′)	1.42(2)	1.52(2)	O(1′)–C(1′)–C(2′)	112(2)	104(1)
C(3′)–O(3′)	1.43(2)	1.46(3)	C(2′)–C(3′)–O(3′)	112(2)	109(2)
C(4′)–C(5′)	1.45(2)	1.66(3)	C(4′)–C(3′)–O(3′)	113(1)	109(2)
C(5′)–O(5′)	1.38(2)	1.46(2)	C(3′)–C(4′)–C(5′)	111(1)	109(2)
O(5′)–P	1.59(1)	1.63(1)	O(1′)–C(4′)–C(5′)	110(1)	103(2)
P–O(6)	1.59(1)	1.49(1)	C(4′)–C(5′)–O(5′)	114(2)	96(2)
P–O(7)	1.51(2)	1.50(1)	C(5′)–O(5′)–P	122(1)	119(1)
P–O(8)	1.53(1)	1.49(2)	O(5′)–P–O(6)	104.8(7)	108.2(7)
N(1)–C(2)–N(3)	116(2)	114(2)	O(5′)–P–O(7)	102.9(8)	99.9(8)
C(2)–N(3)–C(4)	123(2)	126(2)	O(5′)–P–O(8)	108.7(7)	106.1(9)
N(3)–C(4)–C(5)	118(2)	115(2)	O(6)–P–O(7)	115.9(8)	111.1(8)
C(4)–C(5)–C(6)	119(2)	121(2)	O(6)–P–O(8)	107.4(8)	116.1(10)
C(5)–C(6)–N(1)	123(2)	120(2)	O(7)–P–O(8)	116.3(8)	113.9(10)

* Labelled atoms are identical with those in Figure 3.

or ' base N(7) plus phosphate' metal-binding modes are common, and for cytidine nucleotides ' base N(3) [or N(3) + O(2)] plus phosphate ' * is a rule.[2c]

In contrast, metal binding to the uracil base is only rarely observed. This finding suggests that uracil is only weakly co-ordinating to metal ions, presumably due to the N(3) proton present at pH < 9.[14] Therefore, the ' phosphate only ' metal-binding mode may be a general rule for metals interacting with UMP, dUMP, and probably also with TMP.

This scheme also provides an explanation for the destabilization of ordered (double helical) polyuridylic acid in the presence of high concentrations of Cd ions [15] which contrasts the usually observed stabilization of helical polynucleotide structures by alkali or alkaline-earth metal ions. It appears that local formation of Cd–phosphate clusters as found in the present complexes leads to the breakdown of ordered struc-

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* An exception is [Mn(5′-CMP)(H_2O)]·1.5H_2O (5′-CMP = cytosine 5′-monophosphate),[13] showing 'base O(2) plus phosphate' bonding.

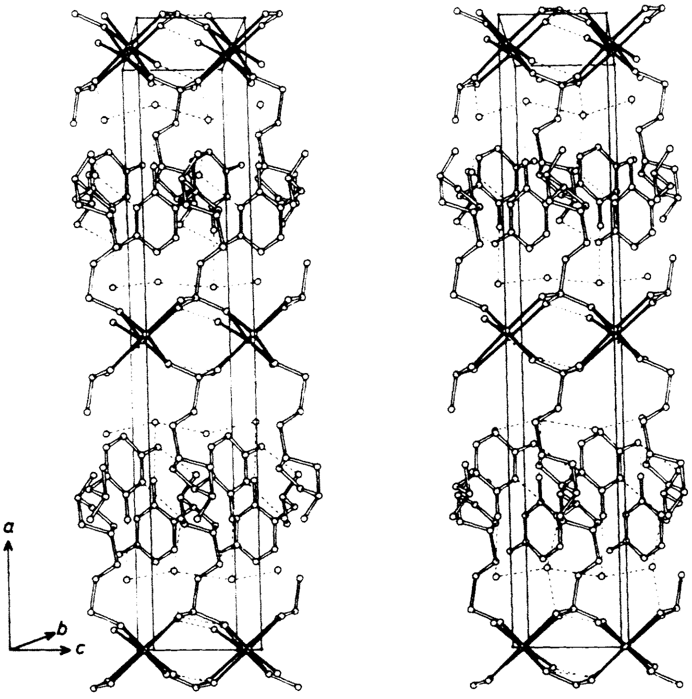

Figure 3. A stereoscopic view of the molecular packing along *b* for [Cd(5′-UMP)$(H_2O)_2$]·$2H_2O$ (1). Broken lines show hydrogen bonds (also in Figures 4 and 5)

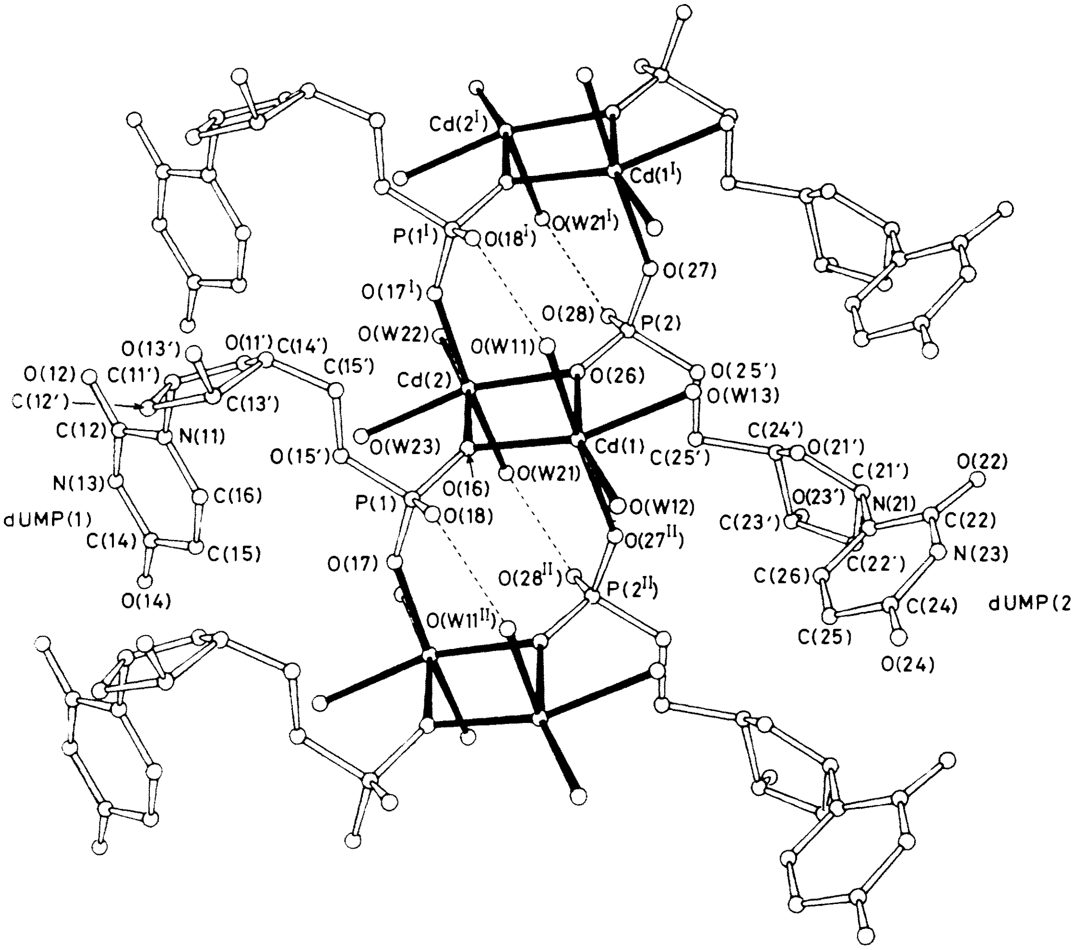

Figure 4. A segment of the polymeric [{Cd_2(5′-dUMP)$_2(H_2O)_6$}$_n$] structure, showing the formation of a column of metal–phosphate clusters from which the sugar–base moieties project outwards in a parallel fashion. The two dUMP molecules adopt rare sugar puckerings and different conformations about the C(4′)–C(5′) bonds: *endo*-O(1′) and *gauche–gauche* for dUMP(1) and *exo*-C(4′) and *gauche–trans* for dUMP(2). Symmetry operations: I *x*, *y*, *z* − 1; II *x*, *y*, 1 + *z*

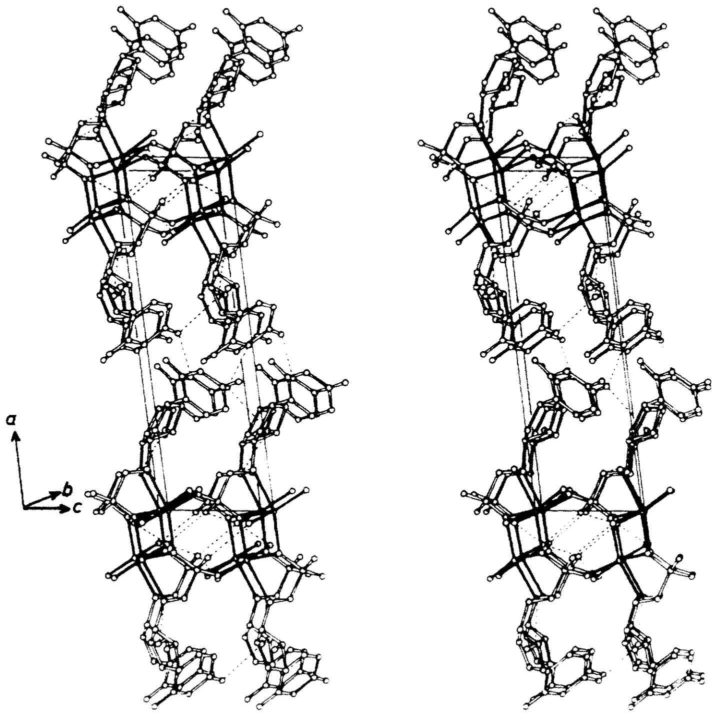

Figure 5. A stereoscopic view of the molecular packing along *b* for $[Cd_2(5'\text{-dUMP})_2(H_2O)_6]$ (2)

Table 6. Hydrogen-bonding [a] and base–sugar O(1′) contacts (Å) with estimated standard deviations in parentheses for $[Cd(5'\text{-UMP})(H_2O)_2]\cdot 2H_2O$ (1)

(*a*) Hydrogen-bonding contacts [b]

N(3) ··· O($3'^{\mathrm{IV}}$)	2.79(3)	O(W2) ··· O(8^{I})	2.73(3)
O(2′) ··· O(4^{V})	2.72(3)	O(W3) ··· O(7)	2.85(3)
O(3′) ··· O(W3)	2.72(3)	O(W3) ··· O(W4)	3.15(6)
O(W1) ··· O(7^{I})	2.93(3)	O(W4) ··· O($\mathrm{W3}^{\mathrm{VI}}$)	2.92(6)
O(W1) ··· O($\mathrm{W4}^{\mathrm{I}}$)	2.64(6)	O(W4) ··· O(2^{VII})	2.86(5)

(*b*) Base–sugar O(1′) contacts [b]

O(1′) ··· N(1^{VI})	3.34(3)	O(1′) ··· C(4^{VI})	3.62(3)
O(1′) ··· C(2^{VI})	3.11(3)	O(1′) ··· C(5^{VI})	3.73(4)
O(1′) ··· N(3^{VI})	3.26(3)	O(1′) ··· C(6^{VI})	3.63(3)

[a] Contacts below 3.2 Å. [b] Symmetry operations: I $x, y, z - 1$; IV $\frac{1}{2} - x, y - \frac{1}{2}, -z$; V $\frac{1}{2} - x, \frac{1}{2} + y, 1 - z$; VI $x, y, 1 + z$; VII $\frac{1}{2} - x, \frac{1}{2} + y, 1 - z$.

Table 7. Hydrogen-bonding contacts [a,b] (Å) with estimated standard deviations in parentheses for $[Cd_2(5'\text{-dUMP})_2(H_2O)_6]$ (2)

N(13) ··· O(24^{III})	2.88(2)	N(23) ··· O(14^{IV})	2.97(2)
O(13′) ··· O(14^{V})	2.78(2)	O(23′) ··· O(24^{VI})	3.13(4)
O(W11) ··· O(18^{I})	2.67(2)	O(W21) ··· O(28^{II})	2.62(2)
O(W11) ··· O(28^{VII}) [c]	3.02(3)	O(W21) ··· O(18^{VIII}) [c]	2.99(2)
O(W11) ··· O($\mathrm{W21}^{\mathrm{VII}}$)	2.79(2)		
O(W12) ··· O(28^{IX}) [c]	2.76(2)	O(W22) ··· O(18^{VI}) [c]	2.74(2)
O(W13) ··· O($23'^{\mathrm{VII}}$)	2.91(3)	O(W23) ··· O($13'^{\mathrm{VIII}}$)	2.78(2)
O(W13) ··· O(25′)	3.03(2)	O(W23) ··· O(15′)	2.88(2)

[a] Contacts below 3.2 Å. [b] Symmetry operations: I $x, y, z - 1$; II $x, y, 1 + z$; III $x - 1, y - 1, z - 1$; IV $1 + x, 1 + y, z$; V $x, 1 + y, z - 1$; VI $x, y - 1, z - 1$; VII $x, 1 + y, z$; VIII $x, y - 1, z$; IX $x, 1 + y, 1 + z$. [c] Phosphate oxygen O(18) bridges to water ligands O(W21) and O(W22) of an adjacent metal–phosphate clustering column and O(28) to O(W11) and O(W12) of another one, thereby connecting neighbouring columns.

Table 8. Torsion angles (°) involving ribose rings and phosphate groups * in complexes (1) and (2)

	Complex (1)	Complex (2) dUMP(1)	dUMP(2)
C(2)–N(1)–C(1′)–O(1′) (χ_{CN})	−172	−125	−124
C(6)–N(1)–C(1′)–O(1′)	12	63	59
N(1)–C(1′)–C(2′)–C(3′)	87	124	124
N(1)–C(1′)–O(1′)–C(4′)	−110	−136	−150
C(2′)–C(1′)–O(1′)–C(4′) (τ_0)	12	−13	−30
O(1′)–C(1′)–C(2′)–C(3′) (τ_1)	−33	6	6
C(1′)–C(2′)–C(3′)–C(4′) (τ_2)	40	3	17
C(2′)–C(3′)–C(4′)–O(1′) (τ_3)	−35	−11	−38
C(3′)–C(4′)–O(1′)–C(1′) (τ_4)	13	15	42
O(1′)–C(1′)–C(2′)–O(2′)	86		
C(4′)–C(3′)–C(2′)–O(2′)	−73		
C(1′)–C(2′)–C(3′)–O(3′)	165	126	134
O(1′)–C(4′)–C(3′)–O(3′)	−155	−133	−154
C(1′)–O(1′)–C(4′)–C(5′)	139	139	156
C(2′)–C(3′)–C(4′)–C(5′)	−159	−135	−148
O(3′)–C(3′)–C(4′)–C(5′) (ψ')	81	104	96
O(1′)–C(4′)–C(5′)–O(5′) (φ_{OO})	−68	−51	66
C(3′)–C(4′)–C(5′)–O(5′) ($\varphi_{OC} = \psi$)	52	73	178
C(4′)–C(5′)–O(5′)–P (φ)	−172	−177	174

* Symbols used to define torsion angles are those given in ref. 10.

tures rather than the often discussed metal–base interactions. The latter are observed in connection with other polynucleotides in which Cd binds to bases.[16] The destabilization of ordered polynucleotide structures by Cd binding to phosphates or bases may be associated with the decrease of fidelity of DNA synthesis [17] and, consequently, be responsible for its mutagenic and carcinogenic properties.[17]

Metal–phosphate cluster formation could also be involved in nucleotide transport across membranes by metal ions.[18] The local neutralization of the charge of a nucleotide by metal–

phosphate complexation is favourable for nucleotide diffusion into the neutral lipid bilayer, and could play a role whenever a nucleotide or polynucleotide has to cross a hydrophilic/hydrophobic contact surface.

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