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Pyrazolylborate–Zinc–Nucleobase-Complexes, 2:[1] Preparations and Structures of $Tp^{Cum,Me}Zn$ and $Tp^{Ph,Me}Zn$ Complexes

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The interactions of the nine most significant nucleobases (thymine, uracil, dihydrouracil, cytosine, adenine, guanine, diaminopurine, xanthine, hypoxanthine, in their deprotonated forms) with zinc and with themselves in pyrazolylborate zinc complexes $Tp^{Cum,Me}Zn$–base and $Tp^{Ph,Me}Zn$–base are described. Except for guanine, the complexes Tp*Zn–base could be isolated in all cases. Structure determinations could be performed for seven of the eight product types. Except for dihydrouracil and xanthine, the zinc ion is attached to that nitrogen of the base which in nucleosides bears the sugar moiety. In the solid state, all zinc-bound nucleobases are involved in hydrogen bonding interactions. Except for xanthine, this includes homo base pairing across a crystallographic inversion center.

Introduction

Like several other divalent metals, zinc participates in mutiple functions in gene-related processes and nucleotide chemistry.[2−7] Zinc has structural and functional roles in transcription factors,[8] steroid receptors,[8] nucleic acid binding retroviruses,[5] polymerases (t-RNA, DNA, RNA),[2,5,7] endonucleases,[9] cytidine and adenosine deaminases,[10] aspartate transcarbamoylase,[5] and dihydroorotase.[11] Furthermore, zinc affects the various structures of DNA[12] and of chromatin[13] as well as ribosomes.[14]

Compared to this relevance, the related model chemistry of zinc with small molecule ligands is not very well developed. The most extensive studies were performed by Sigel[6,7,15] and Marzilli.[16,17] Specifically, zinc−nucleobase interactions were studied by Lippert[18] and Dubler,[19] among others.[20] The influence of zinc ions on the melting of DNA was found by Eichhorn[21] and investigated with zinc complexes by Kimura.[22]

Our own contributions to this field originated from our studies on zinc complexes of drug substances, some of which are derivatives of the nucleobases.[23−25] During these studies, it became evident that anionic nitrogen heterocycles, resulting from deprotonation of their NH functions, are favorably

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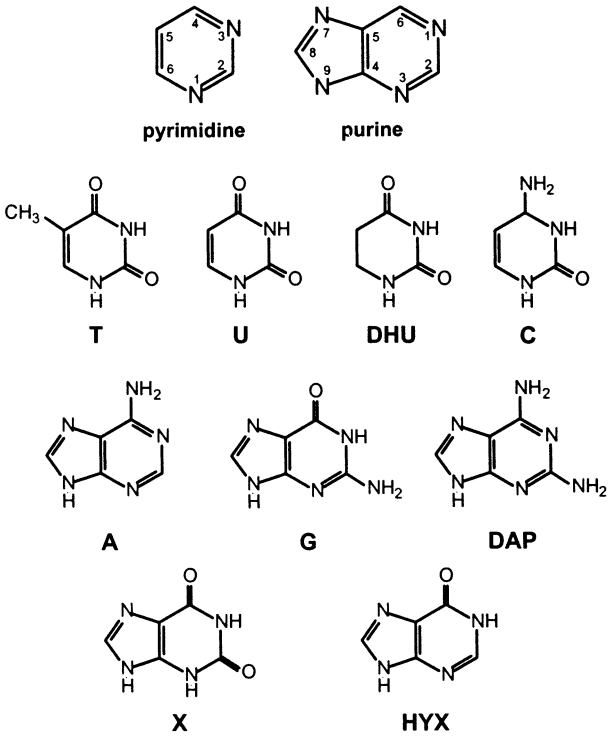
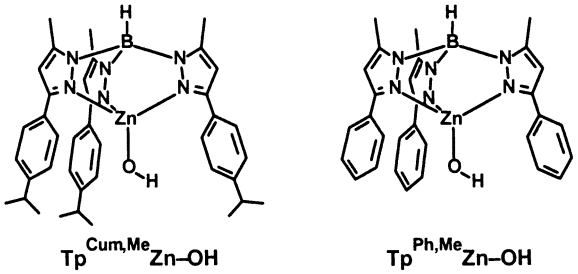
bound to zinc inside the ligand pocket of substituted pyrazolylborates (Tp*). This led to our preliminary investigation of Tp*Zn−uracil and xanthine complexes in the context of Tp*Zn complexes of RNA precursors and analogues thereof.[1]

The present paper is a comprehensive extension of this work. The nine most significant nucleobases (thymine, uracil, dihydrouracil, cytosine, adenine, guanine, diaminopurine, xanthine, and hypoxanthine, whose formulas are given together with the numbering scheme in their basic frameworks of pyrimidine and purine) were tested for their zinc binding. The primary purpose of this study was to find out about the zinc-mediated deprotonation and coordination behavior of the nucleobases. Second, it was to be investigated how the zinc binding affects the base pairing properties, between the zinc−nucleobase complexes themselves as well as between the complexes and additional free nucleobases. This paper reports the preparations and structures of the Tp*Zn−nucleobase complexes. The accompanying paper[26] describes the base pairing studies.



Results and Discussion

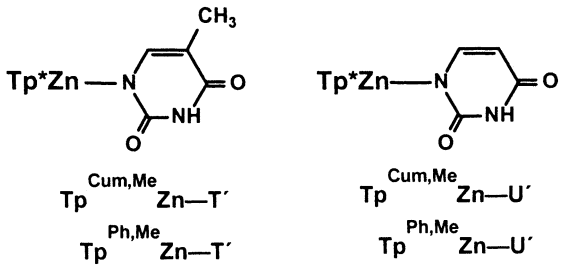
The reagents of choice for the preparation of the Tp*Zn−nucleobase complexes were the hydroxides Tp*Zn−OH. They are strong bases capable of deprotonating the weakly acidic nucleobases in nonpolar media. The resulting intermediates Tp*Zn−OH_2 (which are too labile to be isolated) undergo replacement of the water molecule by the anionic nucleobase.[1] To stabilize the resulting Tp*Zn−nucleobase complexes, it is favorable to encapsulate the nucleobase ligands inside a pocket surrounded by aromatic substituents of the Tp* ligands. For this reason, the cumenyl- and phenyl-substituted Tp*Zn−OH complexes[27,28] were chosen as starting materials.



The reactions between the Tp*Zn−OH complexes and the nucleobases were straightforward. The choice of the solvents (methanol/dichloromethane) was governed by the solubility properties of reagents and products. In the formulations of the nucleobase complexes, the deprotonated nature of the nucleobase ligands is expressed by adding a slanted prime; that is, neutral T is deprotonated to anionic T′, and so forth.

Thymine and Uracil. These two bases which differ only in the substituent at C^5 are the complements of adenine in Watson−Crick base pairing, thymine in DNA and uracil in RNA. Their two NH functions have similar pK_a's, but in nonpolar solvents, the N^1 deprotonated tautomer prevails.[29] Zinc coordination to the anions has been observed so far by other researchers only at N^3.[30,31] We had already described the structure of $Tp^{Cum,Me}Zn-U'$ in which uracil is bound to zinc via N^1.[1] N^1 is also the nitrogen atom of thymine and uracil which in nucleosides bears the sugar moiety.

We have now confirmed that this binding mode is the only one for thymine and uracil in their Tp*Zn complexes. The reactions between both Tp*Zn−OH complexes and the bases have completed the series of the Tp*Zn−thymine and −uracil complexes. The structural assignment of $Tp^{Ph,Me}Zn-U'$ is based on the similarity of its IR and ^{1}H NMR spectra with those of $Tp^{Cum,Me}Zn-U'$.[1] This holds also for both Tp*Zn−T′ complexes. The most significant piece of evidence is the ^{1}H NMR resonance for H^6 of T′ and U′. H^6 is closest to the phenyl groups of the Tp* ligands. Accordingly, its NMR signal has undergone the largest upfield shift in comparison to that for free T′ or U′. On the basis of this and the structure determination of $Tp^{Cum,Me}Zn-U'$,[1] the formulations for the thymine and uracil complexes are as follows:



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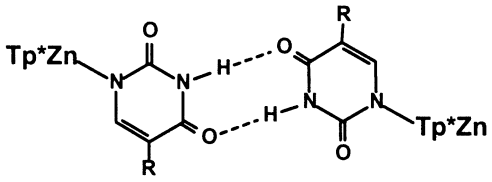
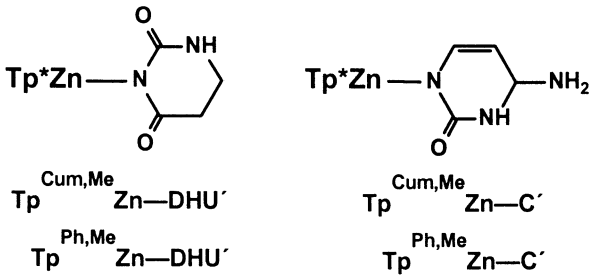
In the solid state, $Tp^{Cum,Me}Zn-U'$ forms dimers by base pairing across a crystallographic inversion center.[1] It is likely that the other three complexes in this group do the same. The evidence for this comes from the behavior of all other Tp*Zn−nucleobase complexes (see later) and from the similarity of the IR data within this group, specifically the NH absorptions which are indicative of hydrogen bonding. Thus, the base pairing scheme for these four complexes is the folowing, with R = H for uracil and R = Me for thymine.



Dihydrouracil and Cytosine. These two bases which can both be derived from uracil show characteristic variations of their NH acidities.[29] Dihydrouracil deprotonates at N^3, flanked by the two carbonyl groups, while deprotonation at N^1 can no longer result in a resonance-stabilized anion. In turn, the same arguments explain why cytosine is deprotonated at N^1. Dihydrouracil is one of the rare nucleobases, being used in t-RNAs, while cytosine is the complement of guanine in Watson−Crick base pairing. In the nucleosides, the sugar moieties are attached to both DHU and C at N^1. There seems to be only one structurally characterized metal complex of DHU in the literature, showing that DHU coordinates via O^4 to $HgCl_2$.[32] Cytosine coordinates to metals perferentially via N^3,[18,33,34] while, in the only structurally characterized complex of anionic cytosine, CH_3Hg-C',[35] binding to mercury occurs via N^1.

While the preparations of Tp*Zn−DHU′ from Tp*Zn−OH posed no problem, pure complexes Tp*Zn−C′ could not be obtained this way, possibly because cytosine is not acidic enough to be completely deprotonated by Tp*Zn−OH. We therefore resorted to using the stronger bases Tp*Zn−H.[36] The yields of the four complexes Tp*Zn−DHU′ and Tp*Zn−C′ were only mediocre because of the purification procedure. The spectra of the products indicated that the anionic nucleobases are attached to zinc via the nitrogen atoms resulting from deprotonation of the most acidic NH functions, that is, N^3 of DHU′ and N^1 of C′. For Tp*Zn−DHU′, this can be deduced from the fact that both ν(CO) bands in the IR spectra are shifted by 30−50 cm^{-1} to lower wavenumbers in comparison to those of free DHU. For Tp*Zn−C′, it is again evident from the upfield shift of almost 1 ppm for the ^1H NMR resonance of the proton at C^6 in comparison to that of free cytosine. Thus, while in the Tp*Zn−C′ complexes the zinc ion is attached to the same nitrogen as the sugars in the nucleosides, the Tp*Zn-DHU′ complexes are exceptions of the rule, having zinc attached to N^3.



The structure determinations of $Tp^{Ph,Me}Zn-DHU'$ and $Tp^{Ph,Me}Zn-C'$ (for details, see Supporting Information) confirmed these assignments. The Zn−N bond lengths are 1.90 Å for DHU′ and 1.95 Å for C′; in $Tp^{Ph,Me}Zn-C'$, there is also a weak Zn−O interaction (2.68 Å). Bond lengths and angles of the nucleobases are very close to those in free DHU[37] and C.[38] The crystals of $Tp^{Ph,Me}Zn-DHU'$ contain two independent complex molecules, representing two possible conformations of the DHU ring. One of these is involved in hydrogen bonding via O^2 to a methanol molecule. The other shows the common feature of all these complexes, that is, dimerization by hydrogen bonding across a crystallographic inversion center, linking N^1 of one molecule with O^2 of the other, cf. Figure 1. Likewise, symmetrical base pairing occurs in the dimers of $Tp^{Ph,Me}Zn-C'$, linking O^2 of one molecule with the external NH_2 group of the other, cf. Figure 2. The observed type of dimerization for DHU is the same as in free DHU,[37] while in free C the symmetrical base pairing involves N^1 and O^2.[38] It may be that $Tp^{Cum,Me}Zn-C'$ displays yet another type of hydrogen bonding, as its spectra differ significantly from those of $Tp^{Ph,Me}Zn-C'$, unlike the situation for the complexes with T′, U′, or DHU′. Just like the different mode of zinc binding for U′ and DHU′, this indicates that only small energy differences govern the choices between the possible bonding modes.

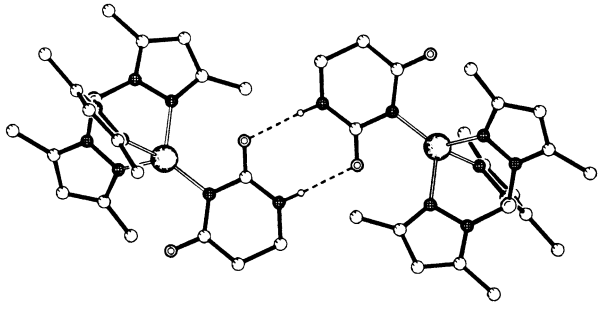


Figure 1. Dimerization of $Tp^{Ph,Me}Zn-DHU'$ in the solid state (aryl groups omitted for clarity).

Adenine, Guanine, and Diaminopurine. Adenine and guanine are two purine bases of the Watson−Crick scheme and hence were major objects of this study. Of the many

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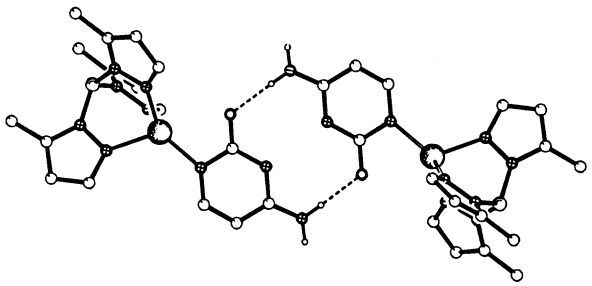
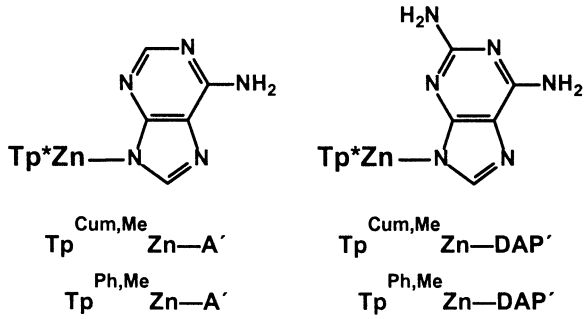


Figure 2. Dimerization of $Tp^{Ph,Me}Zn-C'$ in the solid state (aryl groups and hydrogen-bonded solvent molecules omitted for clarity).

possible tautomers of the nucleobases themselves, those with the proton at N^9, as shown previously, seem to be preferred.[29,33] N^9 is also the point of attachment of the sugars in adenine and guanine nucleosides. While several metal complexes of adenine are known,[16,33] the coordination chemistry of guanine is not well developed.[33,39] N^9 seems to be the preferred donor atom in metal complexes of neutral[16,33] and anionic[40−42] adenine. The only structurally characterized zinc complex, $Zn(AH)Cl_3$,[43] is one of protonated adenine and has the zinc ion attached at N^7, as is the case in the analogous guanine complex $Zn(GH)Cl_3$.[44]

It turned out that we too were unable to prepare zinc−guanine complexes, even when using deprotonated guanine as the reagent. The main reason for this seems to be the extreme stability of guanine in the solid state which expresses itself in the low solubility and high melting point of guanine which in turn result from a very favorable hydrogen bonding network.[45] To compensate for this failure, we used the nonnatural nucleobase diaminopurine which bears an amino substituent at C^6 in place of the carbonyl function of guanine and which has a better solubility. It is known that DAP has very good base pairing properties.[46] We are not aware, however, of any metal−DAP complexes.

Both Tp*Zn−A′ complexes resulted in good yields from Tp*Zn−OH and adenine, as did both Tp*Zn−DAP′ complexes from Tp*Zn−OH and diaminopurine. The attachment of zinc to N^9 of adeninate could be deduced with some certainty from the ^1H NMR data. Again, both the CH resonances at C^2 and C^8 show a large upfield shift upon coordination. While the shift at C^8 does not allow us to distinguish between N^7 or N^9 coordination, that at C^2 favors zinc binding to N^9. Similar conclusions cannot be drawn for diaminopurinate, as C^2 bears the amino group. Here, the structure determination had to prove that zinc is attached at N^9. The spectral similarities within the pairs of A′ and DAP′ complexes show furthermore that the binding modes are the same in all four cases. Therefore, in this group, again the zinc ion in the complexes is attached to the same nitrogen atom as the sugars in the nucleosides.



Because of the uncertainties in the spectral assignments, the structure determinations of $Tp^{Ph,Me}Zn-A'$ and $Tp^{Ph,Me}Zn-DAP'$ (for details, see Supporting Information) were essential in these cases, confirming the $Zn-N^9$ attachments. The Zn−N bond lengths are 1.92 Å in the A′ and 1.93 Å in the DAP′ complex. The purine rings in both complexes are planar and practically undistorted in comparison to other adenine or diaminopurine derivatives.[46−48] The most attractive feature of both structures is again the dimerization of the complexes by means of hydrogen bonding across the inversion centers. The double bridge for the A′ complex connecting each N^1 with N^6 of the opposing molecule represents one of the six possible dimerization modes of adenine and occurs frequently in adenine derivatives.[46] The dimerization of the DAP′ complex follows the same scheme of mutual hydrogen bonds between N^1 and N^6. This type of base pairing has not been observed before for DAP derivatives which prefer triple hydrogen bonds involving both amino groups and the N^1 atom.[48] It might occur for analogous guanine complexes, as evidenced by the dimerization of the Tp*Zn−U′ complexes.[1] Thus, DAP, being similar to both adenine and guanine, has served its purpose in this study. Figures 3 and 4 show the complex dimers.

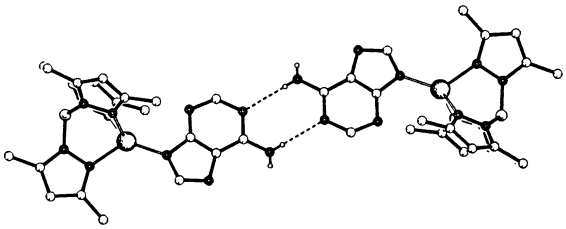


Figure 3. Dimerization of $Tp^{Ph,Me}Zn-A'$ in the solid state (aryl groups and hydrogen-bonded solvent molecules omitted for clarity).

Xanthine and Hypoxanthine. These two nucleobases are less relevant as constituents of DNAs or RNAs, but they are key intermediates in the de novo biosynthesis and the catabolism of the purine bases. Metalloenzymes including zinc enzymes are involved in several steps of their biochemical interconversions. This and the fact that both xanthine and hypoxanthine are close relatives of adenine and guanine

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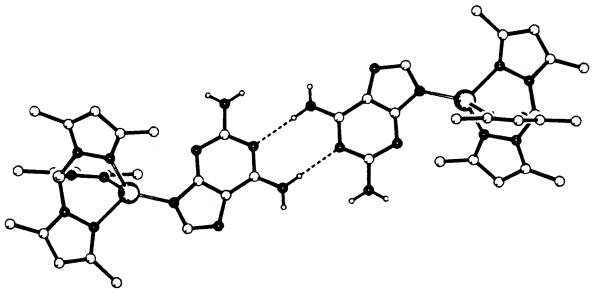
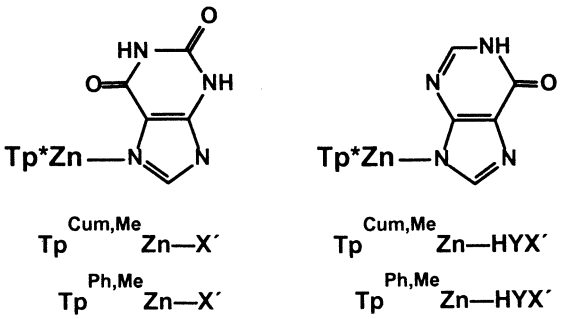


Figure 4. Dimerization of $Tp^{Ph,Me}Zn-DAP'$ in the solid state (aryl groups and hydrogen-bonded solvent molecules omitted for clarity).

were the reasons that we included them in this study. In the preliminary work, we had already prepared $Tp^{Cum,Me}Zn-X'$ and shown that xanthinate is attached to zinc at N^7.[1] In the context of this work, xanthine is the only nucleobase which in its metal-bound form does not induce dimerization via hydrogen bonding in the solid state.[1]

The other xanthinate complex, $Tp^{Ph,Me}Zn-X'$, was now prepared by the standard procedure. Its spectral data are very similar to those of $Tp^{Cum,Me}Zn-X'$, indicating that zinc is again attached at N^7. Thus, the xanthinate complexes join the dihydrouracilate complexes in being exceptions to the rule that zinc is attached at the same nitrogen which bears the sugar moiety in the nucleosides. Just like for dihydrouracil, this may be related to the acid−base properties of the nucleobase. In free xanthine, the imidazole NH function is at N^7,[49] and this may also be the first one to be deprotonated.[50,51] The preference of N^7 over N^9 seems to be subtle, however, as hypoxanthine coordinates via N^9 (see later), and of the two other structurally characterized zinc−xanthine complexes, ZnX_2Cl_2[52] shows N^9 coordination while $Zn(xanthosinate)_2(H_2O)_4$[53] shows N^7 coordination.



Unlike xanthine, hypoxanthine has the N^9H tautomer as the most stable one,[49] and the first deprotonation step also seems to occur at N^9.[51] Our preparations of the Tp*Zn−HYX′ complexes have now confirmed that N^9 is also the nitrogen atom by which hypoxanthinate is attached to zinc. This could only be done by a structure determination of $Tp^{Cum,Me}Zn-HYX'$ (for details see Supporting Information), which showed that the purine ring system is practically planar and that the $Zn-N^9$ distance is 1.94 Å. Again, the preference of N^9 over N^7 for zinc binding must be subtle. Of the two structurally characterized zinc complexes with hypoxanthine ligands, one (a dimer containing bridging hypoxanthine)[54] shows $Zn-N^9$ coordination while the other (an inosine monophosphate derivative)[55] has zinc attached at N^7.

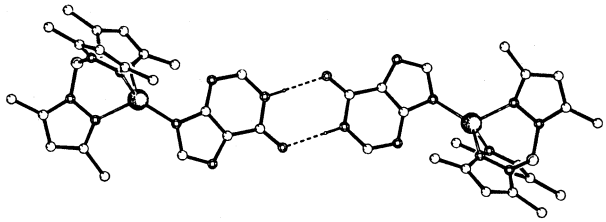


Figure 5. Dimerization of $Tp^{Cum,Me}Zn-HYX'$ in the solid state (aryl groups omitted for clarity).

The ^1H NMR spectra of the Tp*Zn−HYX′ complexes were puzzling initially, seeming to indicate product mixtures or decomposition. It then turned out that the hypoxanthinate complexes are unique in showing the presence of their dimers in solution, in the case of $Tp^{Cum,Me}Zn-HYX'$, even above room temperature. This observation initiated our base pairing studies by NMR methods which are described in the succeeding paper.[26] At low temperatures, the hydrogen-bonded dimers prevail in solution. It can be assumed that they have the same structure as in the solid state, which is shown in Figure 5. Again, cyclic N−H···O bonding across an inversion center is observed, making this type of dimerization which also occurs for the T′, U′, and DHU′ complexes the most frequent one in this series.

Conclusions

The protective pocket provided by the pyrazolylborate ligands Tp* has made it possible to obtain stable and inert zinc complexes Tp*Zn−base of the anionic nucleobases. In all these complexes, the zinc ion is attached to a heterocyclic nitrogen atom. The rather short Zn−N distances (1.90−1.94 Å) indicate strong bonding. In all cases, the zinc-bound nitrogen atom is that which bears the most acidic NH function in the free nucleobases. This implies that except for dihydrouracil and xanthine zinc is bound to that nitrogen which bears the sugar moiety in the nucleosides.

The zinc-bound nucleobases are all involved in hydrogen bonding interactions. With the exception of xanthine, this includes dimerization of the complexes in the solid state via a pair of cyclic hydrogen bonds. The base pairing schemes resemble, but do not always reproduce, those in the free nucleobases. Five cases of cyclic N−H···O bonding and two cases of cyclic N−H···N bonding are observed. There is no case of triple hydrogen bonding. In the case of the Tp*Zn−hypoxanthinate complexes, a monomer−dimer equilibrium has been observed in solution.

Two extensions of this work offer themselves. One is the inclusion of nucleosides and nucleoside analogues. In their

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Table 1. Preparative Details

complex	Tp*Zn−OH mg	Tp*Zn−OH mmol	CH_2Cl_2 mL	nucleobase mg	nucleobase mmol	CH_3OH mL	time, h	recryst solvent	yield mg	yield %	color	mp °C
$Tp^{Cum,Me}Zn-T'$	239	0.35	30	44	0.35	20	4		138	49	colorless	207
$Tp^{Ph,Me}Zn-T'$	251	0.38	50	50	0.39	30	4	benzene	223	78	colorless	186
$Tp^{Ph,Me}Zn-U'$	231	0.35	30	40	0.35	20	4	benzene	183	79	colorless	212
$Tp^{Cum,Me}Zn-DHU'$	223	0.32	40	37	0.32	20	2		54	20	colorless	228
$Tp^{Ph,Me}Zn-DHU'$	248	0.44	50	50	0.44	25	12		43	15	colorless	227
$Tp^{Cum,Me}Zn-A'$	419	0.61	60	89	0.66	40	2		375	74	colorless	211
$Tp^{Ph,Me}Zn-A'$	232	0.32	30	43	0.32	20	2		178	81	colorless	218
$Tp^{Cum,Me}Zn-DAP'$	498	0.72	40	108	0.72	20	48		392	66	pale yellow	228
$Tp^{Ph,Me}Zn-DAP'$	486	0.74	40	111	0.74	20	48		417	77	pale yellow	204
$Tp^{Ph,Me}Zn-X'$	176	0.27	30	42	0.28	30	4		130	69	colorless	>300
$Tp^{Cum,Me}Zn-HYX'$	216	0.31	30	42	0.31	20	4		110	44	colorless	>300
$Tp^{Ph,Me}Zn-HYX'$	270	0.41	40	60	0.44	20	2	CH_3OH/CH_2Cl_2	159	57	colorless	>300

Table 2. Analytical Characterizations

complex	formula mol wt	anal. calcd (found) C	H	N	Zn
$Tp^{Cum,Me}Zn-T'$	$C_{44}H_{51}BN_8O_2Zn$	66.05	6.42	14.00	
	800.14	(65.41)	(6.39)	(13.97)	
$Tp^{Ph,Me}Zn-T'$	$C_{35}H_{33}BN_8O_2Zn\cdot C_6H_6$	65.48	5.23	14.90	8.70
	673.90 + 78.11	(65.43)	(5.21)	(14.83)	(8.98)
$Tp^{Ph,Me}Zn-U'$	$C_{34}H_{31}BN_8O_2Zn\cdot C_6H_6$	65.10	5.05	15.18	
	659.87 + 78.11	(65.38)	(5.06)	(14.72)	
$Tp^{Cum,Me}Zn-DHU'$	$C_{43}H_{51}BN_8O_2Zn\cdot CH_3OH\cdot H_2O$	63.05	6.85	13.37	
	788.13 + 32.04 + 18.02	(62.77)	(6.87)	(13.16)	
$Tp^{Ph,Me}Zn-DHU'$	$C_{34}H_{33}BN_8O_2Zn\cdot 0.5CH_3OH\cdot 0.5CH_2Cl_2$	58.36	5.04	15.55	
	661.89 + 16.02 + 42.97	(58.42)	(5.03)	(15.32)	
$Tp^{Cum,Me}Zn-C'$	$C_{43}H_{50}BN_9OZn$	65.78	6.42	16.06	8.33
	785.13	(65.03)	(6.23)	(15.94)	(7.97)
$Tp^{Ph,Me}Zn-C'$	$C_{34}H_{32}BN_9OZn\cdot 0.5CH_3OH$	61.40	5.08	18.68	
	658.89 + 16.02	(60.94)	(4.88)	(18.73)	
$Tp^{Cum,Me}Zn-A'$	$C_{44}H_{50}BN_{11}Zn\cdot H_2O$	63.89	6.34	18.63	
	809.15 + 18.01	(63.58)	(6.13)	(18.42)	
$Tp^{Ph,Me}Zn-A'$	$C_{35}H_{32}BN_{11}Zn$	61.56	4.72	22.56	9.58
	682.91	(60.91)	(4.67)	(22.27)	(9.50)
$Tp^{Cum,Me}Zn-DAP'$	$C_{44}H_{51}BN_{12}Zn$	64.12	6.24	20.39	
	824.17	(63.94)	(6.15)	(20.50)	
$Tp^{Ph,Me}Zn-DAP'$	$C_{35}H_{33}BN_{12}Zn\cdot CH_3OH$	59.23	5.11	23.03	8.96
	697.93 + 32.04	(58.79)	(5.06)	(23.14)	(8.93)
$Tp^{Ph,Me}Zn-X'$	$C_{35}H_{31}BN_{10}O_2Zn$	60.06	4.46	20.01	
	699.90	(59.31)	(4.48)	(19.30)	
$Tp^{Cum,Me}Zn-HYX'$	$C_{44}H_{49}BN_{10}OZn$	65.23	6.10	17.29	8.07
	810.14	(65.34)	(6.15)	(17.35)	(8.27)
$Tp^{Ph,Me}Zn-HYX'$	$C_{35}H_{31}BN_{10}OZn\cdot H_2O$	59.89	4.74	19.96	
	683.90 + 18.01	(60.29)	(4.53)	(19.93)	

zinc complexes, new modes of attachments will have to be observed, because the preferred nitrogen donor of the nucleobases is blocked. This should also result in new base pairing schemes. The other extension, the detailed investigation of base pairing both between the Tp*Zn−base complexes themselves and between them and additional nucleobases, is the subject of the succeeding paper.[26]

Experimental Section

General Data. All experimental techniques and the standard IR and NMR equipment were as described previously.[56] The Tp*Zn−OH[27,28] and Tp*Zn−H[36] complexes were prepared as described. All nucleobases were obtained commercially.

Preparations. Except for the cytosinate complexes (see later), all nucleobase complexes were prepared according to the following scheme: A solution of the Tp*Zn−OH complex in dichloromethane was added to a suspension of the nucleobase in methanol. After stirring for a given time, the mixture was filtered. The solvents were either partly or completely removed in vacuo. In the former case, cooling to 0 °C led to crystallization of the product; in the latter case, the raw product was recrystallized from another solvent. The products frequently contained the solvent of crystallization. In some cases, the resulting crystals crumbled upon exposure to air, indicating loss of solvent which was then removed completely in vacuo. Samples for elemental analyses and NMR measurements were always subjected to prolonged pumping before the measurements, and solvent contents were then determined by ^1H NMR. Table 1 lists the reaction details. Table 2 gives the analytical characterizations.

$Tp^{Cum,Me}Zn-C'$. The reaction was carried out in an inert gas atmosphere, using cytosine which was dried carefully in vacuo at 120 °C. Cytosine (64 mg, 0.58 mmol) was dissolved in anhydrous methanol (50 mL). $Tp^{Cum,Me}Zn-OH$ (392 mg, 0.58 mmol) was added and the solution refluxed for 24 h. After cooling to 4 °C for 12 h, the precipitate of cytosine was filtered off. Evaporation to 15 mL and cooling to −25 °C yielded 105 mg (23%) of $Tp^{Cum,Me}Zn-C'$ as colorless needles, mp 228 °C, which were dried in vacuo.

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Table 3. Crystallographic Data

	$Tp^{Ph,Me}Zn-DHU'$	$Tp^{Ph,Me}Zn-C'$	$Tp^{Ph,Me}Zn-A'$	$Tp^{Ph,Me}Zn-DAP'$	$Tp^{Cum,Me}Zn-HYX'$
formula	$C_{34}H_{33}BN_8O_2Zn\cdot 0.5CH_3OH\cdot 0.5CH_2Cl_2$	$C_{34}H_{32}BN_9OZn\cdot 2.5CH_3OH$	$C_{35}H_{32}BN_{11}Zn\cdot 5CH_3OH$	$C_{35}H_{33}BN_{12}Zn\cdot 2.5CH_3OH$	$C_{44}H_{49}BN_{10}OZn\cdot 2.8CH_2Cl_2$
MW	720.4	739.0	843.1	778.0	1050.0
space group	$P2_1/c$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$P2_1/n$
Z	8	2	2	2	4
a (Å)	15.714(2)	12.444(3)	10.096(3)	12.394(3)	14.734(3)
b (Å)	17.535(2)	13.659(3)	14.696(3)	12.793(3)	16.701(4)
c (Å)	25.347(3)	13.687(3)	16.347(3)	13.099(3)	21.916(4)
α (deg)	90	115.25(3)	114.14(3)	107.28(3)	90
β (deg)	104.747(3)	107.85(3)	100.39(3)	102.33(3)	92.52(2)
γ (deg)	90	101.67(3)	93.17(3)	97.69(3)	90
V (Å^3)	6754.3(1)	1846.9(7)	2154.4(7)	1893.6(7)	5388(2)
d (calcd) (g cm^{-3})	1.42	1.33	1.30	1.36	1.30
μ (Mo Kα) (mm^{-1})	0.85	0.72	0.63	0.70	0.71
R1[a] (obsd reflns)	0.105	0.073	0.055	0.035	0.086
wR2[a] (all reflns)	0.342	0.227	0.160	0.096	0.282

[a] The R values are defined as $R1 = \sum|F_o - F_c|/\sum F_o$, $wR2 = [\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)]^{1/2}$.

$Tp^{Ph,Me}Zn-C'$. This compound was prepared as before from cytosine (45 mg, 0.41 mmol), $Tp^{Ph,Me}Zn-OH$ (290 mg, 0.45 mmol), and methanol (20 mL). After filtration, the solution was evaporated to 10 mL and then kept in a desiccator for further slow evaporation. A 135 mg (50%) portion of $Tp^{Ph,Me}Zn-C'$ was obtained as a colorless powder, mp 194 °C, which was dried in vacuo.

Spectra. IR spectra were taken from KBr pellets, ^{1}H NMR spectra, from $CDCl_3$ solutions. The following listings give only the relevant data, that is, the IR bands for NH and BH vibrations and in the fingerprint region, the ^{1}H NMR absorptions only for the nucleobases. The ^{1}H NMR data for the pyrazolylborate ligands are virtually identical for their complexes, that is, for $Tp^{Cum,Me}Zn-$base: δ 1.19 [d, $J = 6.9$ Hz, 18H, ^{i}Pr], 2.51 [s, 9H, Me(pz)], 2.84 [sept, $J = 6.9$ Hz, 3H, ^{i}Pr], 6.13 [s, 3H, H(pz)], 7.08 [d, $J = 8.1$ Hz, 6H, C_6H_4], 7.49 [d, $J = 8.1$ Hz, 6H, C_6H_4]. For $Tp^{Ph,Me}Zn-$base: δ 2.56 [s, 9H, Me(pz)], 6.19 [s, 3H, H(pz)], 7.28 [m, 9H, C_6H_5], 7.42 [m, 6H, C_6H_5].

$Tp^{Cum,Me}Zn-T'$ IR: 3423m, b, 2542w, 1658s, 1645s, 1549m, 1519m. NMR: $\delta = 1.49$ [d, $J = 0.9$ Hz, 3H, Me], 5.64 [q, $J = 0.9$ Hz, 1H, H^6], 6.91 [s, 1H, N^{3}H].

$Tp^{Ph,Me}Zn-T'$ IR: 3446w, b, 3178w, 3120m, 2545m, 1676s, 1655s, 1592s, 1545s. NMR: $\delta = 1.48$ [d, $J = 0.8$ Hz, 3H, Me], 5.32 [q, $J = 0.8$ Hz, 1H, H^6], 6.91 [s, 1H, N^{3}H].

$Tp^{Ph,Me}Zn-U'$ IR: 3421m, b, 3123w, 2539w, 1698w, 1665s, 1654s, 1579w, 1560w, 1543m. NMR: $\delta = 4.99$ [d, $J = 7.3$ Hz, 1H, H^5], 5.45 [d, $J = 7.2$ Hz, 1H, H^6], 6.87 [s, 1H, N^{3}H].

$Tp^{Cum,Me}Zn-DHU'$ IR: 3643w (OH), 3445w, 3224w, 2538m, 1693m, 1617w, 1550m, 1521s. NMR: $\delta = 1.71$ [t, $J = 6.5$ Hz, 2H, H^5], 2.89 [m, H^6 together with a Tp* signal].

$Tp^{Ph,Me}Zn-DHU'$ IR: 3435m, 2545m, 1684s, 1639vs, 1546s. NMR: $\delta = 1.63$ [t, $J = 6.5$ Hz, H^5], 2.86 [m, 2H, H^6].

$Tp^{Cum,Me}Zn-C'$ IR: 3466m, 2545m, 1650s, 1600s, 1550s, 1520s. NMR: 4.88 [s, 2H, NH_2], 5.09 [d, $J = 6.2$ Hz, 1H, H^5], 5.78 [broad, 1H, H^6].

$Tp^{Ph,Me}Zn-C'$ IR: 3387m, 3187m, 2547m, 1692vs, 1661m, 1606s, 1544vs. NMR: $\delta = 5.11$ [d, $J = 6.4$ Hz, 1H, H^5], 5.79 [broad, 1H, H^6].

$Tp^{Cum,Me}Zn-A'$ IR: 3477s, 3403s, 3380s, 2545m, 1738w, 1654m, 1626s, 1592m, 1554m. NMR: $\delta = 4.86$ [s, 2H, NH_2], 6.65 [s, 1H, H^8], 7.31 [s, 1H, H^2].

$Tp^{Ph,Me}Zn-A'$ IR: 3476m, 3395w, 3297m, 3142m, 2545m, 1635s, 1592s, 1557m, 1545s. NMR: $\delta = 5.00$ [s, 2H, NH_2], 6.25 [s, 1H, H^8], 7.39 [s, 1H, H^2].

$Tp^{Cum,Me}Zn-DAP'$ IR: 3490m, 3403m, 3193w, 2546m, 1627vs, 1595s, 1574m, 1551w, 1518s. NMR: $\delta = 3.55$ [s, 2H, NH_2], 4.68 [s, 2H, NH_2], 6.27 [s, 1H, H^8].

$Tp^{Ph,Me}Zn-DAP'$ IR: 3649w (H_2O), 3497m, 3455m, 3412s, 3362m, 2543m, 1625s, 1594vs, 1576s, 1545s. NMR: $\delta = 3.71$ [s, 2H, NH_2], 4.86 [s, 2H, NH_2], 5.88 [s, 1H, H^8].

$Tp^{Ph,Me}Zn-X'$ IR: 3422m, 3186m, 3135w, 2541w, 1698s, 1687s, 1677s, 1662s, 1657m, 1588w, 1557m, 1545s. NMR: $\delta = 5.83$ [s, 1H, H^8], 6.58 [s, 1H, N^{3}H], 8.81 [s, 1H, N^{1}H].

$Tp^{Cum,Me}Zn-HYX'$ IR: 3446m, 2551w, 1699m, 1672s, 1645m, 1637w, 1559w, 1546w. NMR: $\delta = 6.42$ [s, 1H, H^8 (monomer)], 6.45 [s, 1H, H^8 (dimer)], 6.69 [d, $J = 3.3$ Hz, 1H, H^2 (dimer)], (H^1-dimer hidden under the Tp* resonances), 8.72 [s, 1H, N^{1}H (monomer)], 10.42 [s, 1H, N^{1}H (dimer)].

$Tp^{Ph,Me}Zn-HYX'$ IR: 3419w, 3194w, 3122w, 2540m, 1685s, 1655s, 1638m, 1591m, 1543m. NMR: $\delta = 6.18$ [s, 1H, H^8], 6.35 [s, 1H, H^2 (monomer)], 6.63 [s, 1H, H^2 (dimer)], 9.54 [s, 1H, N^{1}H (monomer)], 11.01 [s, 1H, N^{1}H (dimer)].

Structure Determinations. The crystals were obtained from the reaction solutions and immediately subjected to the cooling stream of the diffractometer. This way, crumbling of the crystals due to loss of solvent of crystallization was avoided.. The data sets were obtained at 180 K with a Bruker AXS Smart CCD diffractometer and treated without an absorption correction. The structures were solved with direct methods and refined anisotropically using the SHELX program suite.[57] Hydrogen atoms were included with fixed distances and isotropic temperature factors 1.2 times those of their attached atoms. Parameters were refined against F^2. Drawings were produced with SCHAKAL.[58] Table 3 lists the crystallographic data.

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Supporting Information Available: Fully labeled ORTEP plots and X-ray crystallopraphic files in CIF format for the five structure determinations. This material is available free of charge via the Internet at http://pubs.acs.org.

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