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$Zn{-}O_2H_3{-}Zn$: a Coordination Mode of the Hydrolytic Zinc−Aqua Function and a Possible Structural Motif for Oligozinc Enzymes

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Abstract: Reactions of the pyrazolylborates KTp′ with $Zn(ClO_4)_2$ and KOH in a 2:2:1 ratio yield the complexes $[Tp'_2Zn_2O_2H_3]ClO_4$ (**1**) for Tp′ = hydrotris(3-R-5-methylpyrazolyl)borate with R = *p*-isopropylphenyl (**a**), 3-pyridyl (**b**), and 3-(6-methyl)pyridyl (**c**). Their structure determinations have revealed a Zn-OH-H···OH-Zn array (i.e., a bridging $H_3O_2^-$ ligand) in the dinuclear complex cations. The zinc ions in complex **1a** are in a distorted tetrahedral ZnN_3O environment, and those in **1b** and **1c** are in a distorted trigonal bipyramidal ZnN_4O environment due to additional coordination of one pyridyl nitrogen from the opposing Tp′ ligand. In **1b**, one Zn-OH function is involved in a hydrogen bridge to a cocrystallized methanol molecule. The complexes represent a mode of stabilization for the zinc−aqua function in the cationic $Tp'Zn\text{-}OH_2$ species, and they are intermediates in the formation of the stable Tp′Zn-OH complexes. It is suggested that the $Zn\text{-}O_2H_3\text{-}Zn$ unit is present as a structural and possibly functional motif in oligozinc enzymes like phospholipase C or P1 nuclease.

Introduction

The functional unit in hydrolytically active zinc enzymes is a zinc-bound water molecule which is deprotonated near neutral pH to generate the strongly nucleophilic Zn-OH group.[1−4] In terms of simple acid−base theory this means that for a pK_a of 7 exactly 50% of the $Zn\text{-}OH_2$ functions of the enzyme are deprotonated at pH = 7 (i.e., the $Zn\text{-}OH_2$/Zn-OH ratio is 1:1). While this is solely a statistical statement for the active enzymes, it may be significant for small-molecule enzyme models where the chance exists to assess the $L{\cdot}Zn\text{-}OH_2/L{\cdot}Zn\text{-}OH$ interactions or to isolate $(L{\cdot}Zn\text{-}OH_2)(L{\cdot}Zn\text{-}OH)$ species.

The presence of $(L{\cdot}Zn\text{-}OH_2)(L{\cdot}Zn\text{-}OH)$ species is reality in the new class of oligozinc enzymes[5,6] of which phospholipase C,[7] alkaline phosphatase,[8] and P1 nuclease[9] have been identified by crystal structure analyses. All three possess a trinuclear array of metal ions in the active center which contains only zinc ions, except for alkaline phosphatase (Zn_2Mg). For phospholipase C and P1 nuclease, this array can be described by a single formula (Figure 1). All three zinc ions are five-coordinate, the two structural zinc ions Zn1 and Zn3 are bridged by a OH^- ion and by bidentate aspartate, and the catalytic zinc ion Zn2 is only loosely connected to the two others (but bridged to Zn1 and Zn3 by phosphate in the phosphate-inhibited enzyme[10]). The approximate intermetallic distances are Zn1−Zn3 = 3.3 Å, Zn1−Zn2 = 5.8 Å, and Zn3−Zn2 = 4.7 Å. Both ligated water molecules are bound to Zn2, while the OH^- group is bound to Zn1 and Zn3.

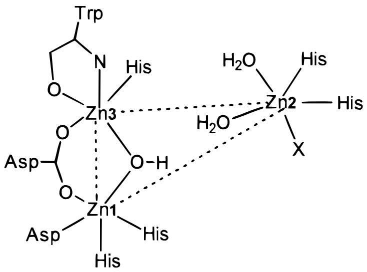

Figure 1. Coordination of the three zinc ions in phospholipase C (X = Glu) and P1 nuclease (X = Asp): Zn1···Zn3 ca. 3.3 Å, Zn1···Zn2 ca. 5.8 Å, Zn2···Zn3 ca. 4.7 Å.

Numerous zinc−aqua complexes have been proposed as models for hydrolytic zinc enzymes,[3,4,11,12] and their pK_a values have been determined and interpreted.[13,14] Recently, more realistic models in the form of Zn-OH complexes have been found and used for stoichiometric as well as catalytic model reactions.[15−20] Along these lines, it has also been observed that

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OH^- is a good bridging ligand in molecular zinc complexes,[21−24] and the above-mentioned Zn1−Zn3 distance of ca. 3.3 Å has been reproduced in Zn-OH-Zn[21−24] as well as in Zn-RCOO-Zn bridged systems.[22,25,26] So far a hydrolytically active model system with a di- or trinuclear zinc core has not been described.

Thus, at the beginning of this work the Zn-OH_2, Zn-OH, and Zn-OH-Zn functions were well-established in classical coordination as well as in enzyme model chemistry. In this paper, we wish to present a further function, Zn-O_2H_3-Zn, which is a combination of Zn-OH_2 and Zn-OH (i.e., a complexed form of the hydrated hydroxide ion) and may reproduce the connection between the catalytic Zn2 ion and the structural Zn1, Zn3 unit in the above-mentioned trimetal enzymes.

Experimental Section

The general experimental techniques and physical measurements were as described before.[27] Reagents were obtained commercially. The potassium salts of the pyrazolylborate ligands (KTp′) were prepared from KBH_4 and the corresponding pyrazole (pz) according to the standardized procedure.[17,28,29]

Caution: Perchlorate salts are dangerous and possibly explosive. If the appropriate safety gear is not available they should be handled in sub-millimolar quantities only.[30]

Complex 1a. A solution of 2.00 g (3.08 mmol) of potassium hydrotris(3-cumyl-5-methylpyrazolyl)borate in 50 mL of dichloromethane was treated dropwise with stirring with a solution of 1.15 g (3.09 mmol) of $Zn(ClO_4)_2 \cdot 6H_2O$ in 10 mL of methanol and then with 56 mg (1.00 mmol) of finely powdered KOH. After 1 h of stirring, the solution was filtered from $KClO_4$ and its volume reduced to 30 mL in vacuo. Crystallization at 4 °C yielded 1.43 g (62%) of **1a** as a colorless powder (mp 167 °C), which was dried in vacuo. Selected IR bands (KBr, cm^{-1}): 3607m br, 3459m br (OH), 2542m (BH), 1550s, 1519s (ring), 1097s, 1066s (ClO). ^1H-NMR ($CDCl_3$, ppm): 0.47 [d, $^3J = 6.9$ Hz, 36H, Me(*i*-Pr)], 2.21 [septet, $^3J = 6.9$ Hz, 6H, CH(*i*-Pr)], 2.45 [s, 18H, Me(pz)], 6.17 [s, 6H, CH(pz)], 6.29 [d, $^3J = 8.2$ Hz, 12H, Ph(3,5)], 6.51 [d, $^3J = 8.2$ Hz, Ph(2,6)]. Anal. Calcd for $C_{78}H_{95}B_2ClN_{12}O_6Zn_2$ (1484.6): C, 63.11; H, 6.45; N, 11.32; Zn, 8.81. Found: C, 62.84; H, 6.49; N, 11.25; Zn, 8.65.

Complex 1b. A solution of 300 mg (0.57 mmol) of potassium hydrotris(3-(3-pyridyl)-5-methylpyrazolyl)borate in 20 mL of dichloromethane and 20 mL of methanol was treated with 213 mg (0.57 mmol) of solid $Zn(ClO_4)_2 \cdot 6H_2O$ and 19 mg (0.29 mmol) of finely powdered KOH. After 2 h of stirring, the solution was filtered from $KClO_4$ and then evaporated to dryness in vacuo. Recrystallization from methanol yielded 230 mg (63%) of **1b** as colorless crystals (mp 185 °C) which lose methanol upon pumping. Selected IR bands (KBr, cm^{-1}): 3380w, br (OH), 2547m (BH), 1601m (ring), 1094s, 1066s (ClO). ^1H-NMR ($CDCl_3$, ppm): 2.62 [s, 18H, Me(pz)], 6.32 [s, 6H, CH(pz)], 7.11 [dd, $^3J_1 = 7.8$ Hz, $^3J_2 = 5.0$ Hz, 6H, H5(py)], 7.67 [d, $^3J = 5.0$ Hz, 6H, H4(py)], 7.76 [d, $^3J = 7.8$ Hz, 6H, H6(py)], 8.77 [s, 6H, H2(py)]. Anal. Calcd for $C_{54}H_{53}B_2ClN_{18}O_6Zn_2 \cdot CH_3OH$ (1238.0 + 32.0): C, 52.01; H, 4.52; N, 19.86; Zn, 10.30. Found: C, 51.71; H, 4.34; N, 19.59; Zn, 10.10.

Complex 1c. A procedure similar to that for **1b** was used with the following compounds: 300 mg (0.53 mmol) of potassium hydrotris-(3-((6-methyl)-3-pyridyl)-5-methylpyrazolyl)borate, 197 mg (0.53 mmol) of $Zn(ClO_4)_2 \cdot 6H_2O$, and 15 mg (0.265 mmol) KOH. Recrystallization from benzene/dichloromethane/ethanol (5:5:1) yielded 250 mg (71%) of **1c** as colorless crystals (mp 191 °C) which lose solvent upon pumping. Selected IR bands (KBr, cm^{-1}): 3380m, br (OH), 2553m (BH), 1609s (ring), 1093m, 1066m (ClO). ^1H-NMR ($CDCl_3$, ppm): 1.82 [s, 18H, Me(py)], 2.62 [s, 18H, Me(pz)], 6.34 [s, 6H, CH(pz)], 6.92 [d, $^3J = 8.0$ Hz, H5(py)], 7.82 [dd, $^3J_1 = 8.0$ Hz, $^3J_2 = 2.2$ Hz, 6H, H4(py)], 8.78 [d, $^3J = 2.2$ Hz, 6H, H2(py)]. Anal. Calcd for $C_{60}H_{65}B_2ClN_{18}O_6Zn_2$ (1322.2): C, 54.50; H, 4.96; N, 19.07; Zn, 9.89. Found: C, 54.29; H, 4.78; N, 19.21; Zn, 9.70.

X-ray Crystallography. Crystals of **1a** were obtained by slow evaporation from ethanol/dichloromethane, and those of **1b** and **1c** from the preparations as described above. The structure determinations revealed that the crystals of **1a** contain half of formula unit per asymmetric unit, those of **1b** one formula unit, half of water molecule, and three methanol molecules, and those of **1c** one formula unit, two water molecules, and one ethanol molecule per asymmetric unit, which was confirmed by ^1H-NMR. Diffraction data were recorded with the $\omega/2\theta$ scan mode on a Nonius CAD4 diffractometer fitted with a molybdenum tube ($\lambda_{K\alpha} = 0.71073$ Å) and a graphite monochromator at 294 K. The data were corrected for absorption using psi scans. The structures were solved by direct methods and refined anisotropically using the SHELX program package.[31] During the refinement, wR2 was optimized according to $wR2 = [\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]]^{1/2}$ with $w = 1/[\sigma^2(F_o^2) + (aP)^2 + bP]$ for $P = (F_o^2 + 2F_c^2)/3$ and a and b as free variables. All hydrogen atoms were included, C−H was fixed at 0.96 Å, and the isotropic temperature factors of the hydrogen atoms were fixed at 1.2 times the value of their attached atom (1.5 times in methyl groups).

The hydrogen atoms of the bridging $H_3O_2^-$ ligands could be located with a reasonable degree of precision in the Fourier maps. All three of them could be refined freely for **1c**. For **1b**, the bridging hydrogen did not refine well. Therefore, it had to be fixed halfway between the two oxygens, while the other hydrogens were again refined freely. For **1a**, the location of the $H_3O_2^-$ hydrogens showed the lowest degree of precision. The bridging hydrogen could be refined only on the inversion center, which does not prove that it is positioned exactly there, and for the other hydrogen, the O−H bond length and the Zn−O−H angle had to be fixed, leaving the torsion angle variable.

In all three structures, the locations of the constituents outside the dinuclear complex cations were not well-defined. In **1a**, the ClO_4^- ion has half occupancy, and unreasonable Cl−O bond lengths and extremely high anisotropic thermal parameters indicated considerable disorder. It was therefore decided to treat it as a rigid body with Cl−O distances variable and to use isotropic temperature factors for the O atoms, at the expense of more than 1% in the *R* value. In **1b**, the methanol molecule “inside” the complex was well-behaved, while low definition and half-occupancy were indicated for the remaining methanol and water molecules. The latter are linked by hydrogen bridges and attached by a hydrogen bridge to N16. The ClO_4^- ion seems to be disordered again but could be refined anisotropically. In **1c**, the ClO_4^- ion is well-behaved. Two locations with half-occupancy were found for the ethanol molecules, which are neither linked to one another nor to the complex cation. The two water molecules were located with full-occupancy; they are hydrogen bridged only to each other.

Table 1 gives a summary of the crystallographic data. The drawings (see below) were produced using the SCHAKAL program.[32]

Results

Treating the anionic tris(pyrazolyl)borate (Tp′) ligands **a**−**c** as their potassium salts with zinc perchlorate hexahydrate in

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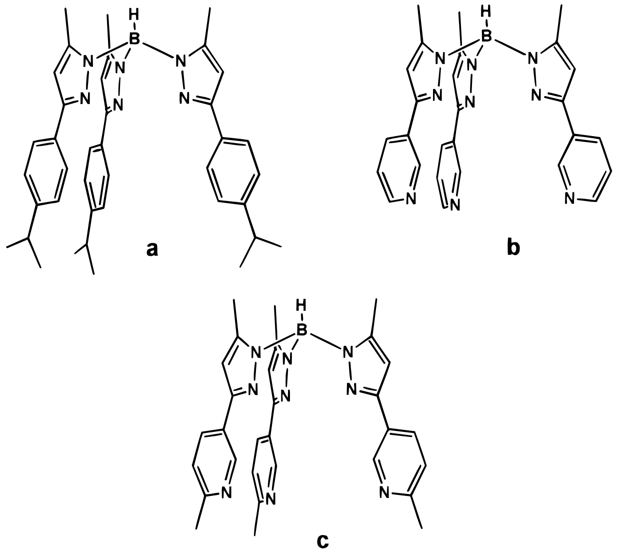
methanol/dichloromethane solutions in the presence of 0.5 equiv of KOH results in the formation of the dinuclear complexes **1a**−**c**. The dinuclear complexes can be recrystallized, but they have a limited persistence in solution. In methanol they undergo a slow conversion to the mononuclear Tp′Zn-OH complexes. For **1a**, this conversion is complete within 24 h,[17] with the liberated acidity being partially used up by hydrolytic destruction of the Tp′ ligand. For **1b** and **1c**, it takes another 0.5 equiv of KOH to bring the conversion to Tp′Zn-OH to completion.[33] In the solid state, complexes **1** are stable for extended periods.



$[Tp'Zn\text{-}O_2H_3\text{-}ZnTp']ClO_4$

1a, Tp′ = **a**
1b, Tp′ = **b**
1c, Tp′ = **c**

The NMR and IR data of complexes **1** (see Experimental Section) confirm the presence of all their constituents (i.e., the intact pyrazolylborate ligands, the OH or OH_2 ligands, and the perchlorate ions). The OH bands in the IR are broad and located at significantly lower wavenumbers than the sharp OH bands of the mononuclear Tp′Zn-OH complexes,[16,17] in accordance with the presence of OH···O hydrogen bridges. The NMR spectra show only one set of proton resonances for all six aryl−pyrazolyl groupings in each case. They also confirm that after prolonged pumping, which makes the crystals of **1b** and **1c** crumble, most of the cocrystallized solvent has been removed. We failed to observe OH signals in the NMR spectra, which in this case may be due to H/D exchange in the solvent $CDCl_3$. But in other solvents, like for our other Zn-OH complexes,[17] the OH NMR resonances are also not observed.

The molecular structures of all three complexes have been determined by X-ray crystallography. The crystallographic details are given in the Experimental Section, including our partially successful efforts in locating and refining the $H_3O_2^-$ hydrogen atom positions. In all three cases, it has been found that in the dinuclear complex cations the two zinc ions are linked by a Zn-OH-H···OH-Zn bridge (i.e., they consist of two molecular units of Tp′Zn-OH held together by an additional proton). Since the bridging hydrogen atoms cannot be located beyond doubt by crystallographic methods, the evidence for their existence rests as much in the presence of the moderately well-located perchlorate ions as in the short central O···O contact distances. For **1b** and **1c**, the possibility exists that one of the "unused" pyridine nitrogen atoms is protonated. There is, however, no evidence for this, neither in terms of an unusual shape or disposition of one of the pyridine rings nor in terms of the linking of the perchlorate ions to any of the pyridine nitrogens by a hydrogen bridge.

Complex **1a** is the simplest of the three complexes, and it shows the essential features of this structural type in the simplest way, (cf. Figure 2 and Table 2). The asymmetric unit of **1a** consits of half of the complex cation and half of the perchlorate anion. The two halves of the complex cation are related by a center of symmetry located halfway between the two oxygen atoms. This results in the whole complex appearing quite symmetrical, but it caused difficulties in finding and refining the perchlorate anion with half-occupancy.

In order to form the central O-H···O bridge, the two Tp′Zn units have to interpenetrate such that each aromatic substituent is placed between two substituents of the opposing Tp′Zn unit. This results in a complete encapsulation of the central $Zn\text{-}O_3H_2\text{-}Zn$ core. For the two Tp′Zn units, the interleaved situation seems to be stress-free, as can be seen from the normal and quite constant Zn−N bond lengths and N−Zn−N angles.[34] Accordingly, there is no feature of the Tp′ ligands in **1a** that deserves further discussion.

The centrosymmetry of the complex cations does not imply that the two main axes of the Tp′Zn units (i.e., the B−Zn lines) are colinear. Neither does it imply that each zinc ion is coordinated with trigonal symmetry. As can be seen from the O−Zn−N angles, the O atom is bent away from the trigonal axis. This is possibly, but not necessarily, a result of the intertwining of the two complex halves. We have observed similar distortions in intertwined (e.g., Tp′Zn-O-ZnTp′)[35] as well as in simple (e.g., Tp′Zn-OC(O)R)[17,33,36] zinc complexes of ligand **a**. The Zn−O bond length (1.87 Å), although quite short, is also normal for Tp′Zn-OX complexes.[15−17] Thus, the ZnN_3O coordination in **1a** is, within the limits of tolerance, of the usual distorted tetrahedral type found in TpZn-X complexes.

The central Zn-O-O-Zn arrangement is strictly transoid, due to the center of symmetry. This yields the maximum possible Zn−Zn distance for such an arrangement, in this case 5.76 Å. The O···O distance (2.40 Å) represents a very strong hydrogen bond. If this O-H···O bond is assumed to be linear (i.e., the bridging hydrogen is located exactly on the inversion center), then it defines Zn−O−H angles which are identical to the Zn−O1−O1′ angle of 138°. With the locations found for the H atoms, the coordination of the O atoms is that of a flat trigonal pyramid.

The structure of complex **1b** differs significantly from that of **1a** (cf. Figure 3 and Table 3). While the interpenetration of the two Tp′ ligands is generally similar to that in **1a**, the encapsulation of the two Zn-OH units is even more pronounced. This results from coordination of one pyridyl nitrogen from each Tp′ ligand to the opposing zinc ion, and in addition, one of the methanol molecules of cocrystallized solvent forms a hydrogen bridging link between one pyridyl nitrogen and the opposing Zn-OH group (O2−O7 = 2.69 Å). The other Zn-OH group, in turn, is connected by a weak hydrogen bond to a pyridyl nitrogen (O1−N17 = 3.03 Å). The remaining two methanol and one-half water molecules per formula unit of **1b** are located outside the dinuclear complex (see Experimental Section).

As a consequence of the additional pyridine ligation, the zinc ions in **1b** are five-coordinate. The inspection of Table 3 shows that their geometry can be described as trigonal bipyramidal to

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Table 1. Crystallographic Data for the Three Complexes

	1a	**1b**	**1c**
formula	$C_{39}H_{47}BN_6OZn\cdot0.5HClO_4$	$C_{54}H_{52}B_2N_{18}O_2Zn_2\cdot HClO_4\cdot 3CH_3OH\cdot0.5H_2O$	$C_{60}H_{64}B_2N_{18}O_2Zn_2\cdot HClO_4\cdot 2H_2O\cdot C_2H_5OH$
mol. wt.	742.3	1343.1	1404.2
color	colorless	colorless	colorless
size [mm]	0.6 × 0.6 × 0.6	0.6 × 0.5 × 0.5	0.7 × 0.6 × 0.6
crystal system	orthorhombic	triclinic	monoclinic
space group	*Pbca*	$P\bar{1}$	$P2_1/n$
Z	8	2	4
a [Å]	19.092(3)	15.068(1)	16.431(2)
b [Å]	19.716(3)	15.601(1)	21.604(2)
c [Å]	21.550(3)	17.734(1)	20.159(2)
α [deg]	90	99.57(1)	90
β [deg]	90	105.19(1)	97.55(1)
γ [deg]	90	113.43(1)	90
V [Å^3]	8112(2)	3515.1(4)	7094(1)
d_{calc} [g cm^{-3}]	1.22	1.27	1.32
d_{obs} [g cm^{-3}]	1.20	1.24	1.30
μ [mm^{-1}]	0.68	0.78	0.78
T_{min}/T_{max}	0.76/0.98	0.89/0.96	0.82/0.90
2Θ range [deg]	4.6−47	4.4−50	4.5−52
range			
h	0−21	−17−17	−20−0
k	0−21	18−18	0−26
l	−24−0	0−21	−24−24
reflns measd	5859	12703	14432
indep. reflns	5859	12262	13932
obsd reflns [$I \geq 2\sigma(I)$]	3481	5881	6630
parameters	459	811	857
R (unweighted)	0.069	0.068	0.080
wR2	0.171	0.170	0.208
GOF	1.051	1.04	1.08
res. electron density [e/Å^3]	+1.5 −0.5	+0.9 −0.4	+1.4 −0.4

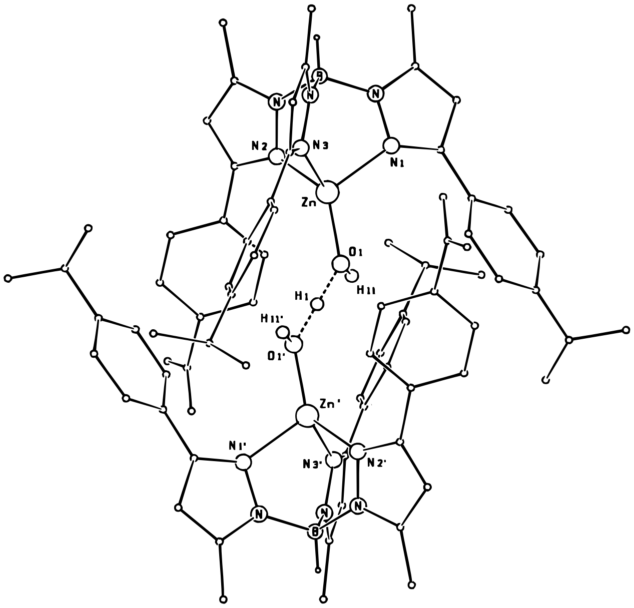

Figure 2. Molecular structure of the cation of complex **1a**.

Table 2. Essential Bond Distances (Å) and Angles (deg) in **1a**

Zn−O1	1.873(5)	O1−Zn−N1	116.9(3)
Zn−N1	2.024(6)	O1−Zn−N2	128.3(2)
Zn−N2	2.008(6)	O1−Zn−N3	121.5(3)
Zn−N3	2.027(6)	N1−Zn−N2	94.6(2)
O1···O1′	2.399(11)	N1−Zn−N3	96.2(2)
Zn···O1′	3.995(5)	N2−Zn−N3	91.9(2)
Zn···Zn′	5.760(2)	Zn−O1−O1′	138.2(4)
O1−H1	0.85(fix)	Zn−O1−H11	108.9(2)
O1−H11	1.199(5)	H1−O1−H11	75.0(3)

a good approximation. The expansion of the coordination sphere in zinc complexes of highly substituted Tp ligands is untypical because the voluminous substituents on the pyrazoles block the space for additional ligands.[29,34] However, we have previously observed that chelating ligands which are essentially planar can form five-coordinate Tp′Zn(L-L) complexes because of favorable interlocking between the substituents of the pyrazoles.[36,37] The trigonal bipyramidal coordination of both zinc ions in **1b** goes along with an unsymmetrical binding of the Tp′ ligands to zinc (i.e., one Zn−N(pyrazole) bond is very much longer than the other two), again as observed before for Tp′Zn(L-L) complexes.[36,37] A second very long Zn-N bond for both zinc ions involves the pyridine nitrogen, thus defining the axis of the trigonal bipyramid.

Despite the very different coordinative environment of the zinc ions in **1a** and **1b**, the $H_3O_2^-$ ligands encapsulated in this environment have similar shapes and bonding types. The O···O distance in **1b** (2.45 Å) is only a little longer than that in **1a**, and the bridging H atom can be refined halfway along the O···O line. The Zn−O−O angles (126 and 134°) are slightly, but not significantly, smaller than those in **1a**, and the central axes of the two Tp′ ligands (i.e., the B−Zn lines) point away from each other in a characteristic fashion again. Complex **1b** contains an internal reference for the strength of the central O-H···O hydrogen bridge in the form of the O2-H···O7 and O1-H···N17 bridges, which are both approximately 0.25 Å longer.

The major difference between the $H_3O_2^-$ units in **1a** and **1b** lies in the involvement of the latter in the O2-H···O7 and O1-H···N17 bridges and in the disposition of the zinc ions. While the Zn-O···O-Zn arrangement in **1a** is exactly anti (dihedral angle 180°), it is of the gauche type in **1b** (dihedral angle 65°). This results in a considerable shortening of the Zn···Zn distance (5.12 Å in **1b**).

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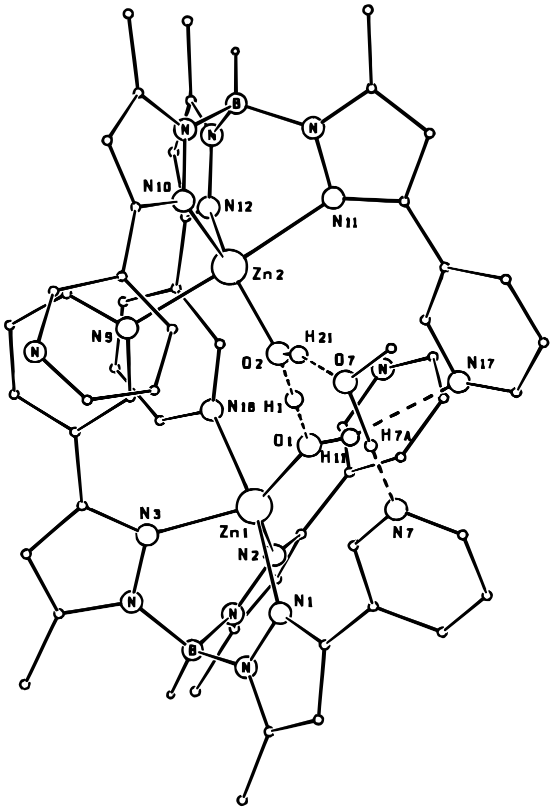

Figure 3. Molecular structure of the cation of complex **1b**.

Table 3. Essential Bond Distances (Å) and Angles (deg) in **1b**

Zn1−O1	1.872(6)	H11−O1−H1	92.0(60)
Zn1−N1	2.308(7)	H21−O2−H1	117.0(67)
Zn1−N2	2.014(6)	O1−Zn1−N1	100.8(3)
Zn1−N3	2.049(7)	O1−Zn1−N2	132.7(3)
Zn1−N18	2.358(7)	O1−Zn1−N3	129.2(3)
Zn2−O2	1.916(6)	O1−Zn1−N18	90.0(3)
Zn2−N10	2.028(6)	N1−Zn1−N2	86.0(3)
Zn2−N11	2.310(7)	N1−Zn1−N3	85.8(3)
Zn2−N12	2.049(6)	N1−Zn1−N18	169.1(2)
Zn2−N9	2.230(7)	N2−Zn1−N3	97.8(3)
O1···O2	2.451(8)	N2−Zn1−N18	87.7(2)
Zn1···O2	3.984(6)	N3−ZN1−N18	86.3(3)
Zn2···O1	3.896(5)	O2−Zn2−N10	126.0(3)
Zn1···Zn2	5.118(1)	O2−Zn2−N11	95.0(2)
O2···O7	2.691(9)	O2−Zn2−N12	136.4(3)
O7···N7	2.719(11)	O2−Zn2−N9	89.2(2)
O1···N17	3.034(11)	N10−Zn2−N11	89.6(2)
Zn1−O1−O2	133.9(3)	N10−Zn2−N12	97.5(2)
Zn2−O2−O1	125.9(3)	N10−Zn2−N9	94.1(3)
Zn1−O1−H11	137.8(57)	N11−Zn2−N12	81.8(3)
Zn2−O2−H21	115.2(59)	N11−Zn2−N9	171.3(2)
Zn1−O1−H1	134.1(30)	N12−Zn2−N9	89.9(3)
Zn2−O2−H1	125.8(30)		

The structure of complex **1c** is a variation of that of **1b** (cf., Figure 4 and Table 4). Again, the zinc ions are five-coordinate due to attachment of one pyridyl nitrogen each, and again their geometry is that of a slightly distorted trigonal bipyramid, the axis of which is defined by the Zn-N bonds to one pyrazole and the pyridine nitrogen. This time, the cocrystallized solvent molecules (two H_2O and one C_2H_5OH per formula unit) are not involved in hydrogen bridging to the molecular core, but both Zn-OH functions are involved in weak intracore hydrogen bridges to pyridyl nitrogen atoms (O1−N18 = 2.85 Å, O2−N8 = 2.86 Å).

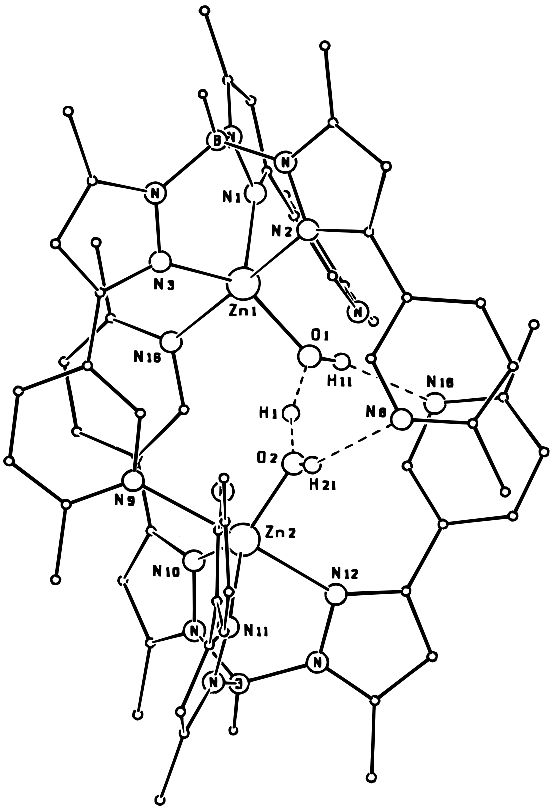

Figure 4. Molecular structure of the cation of complex **1c**.

Table 4. Essential Bond Distances (Å) and Angles (deg) in **1c**

Zn1−O1	1.888(6)	Zn2−O2−H21	121.3(81)
Zn1−N1	2.012(6)	Zn2−O2−H1	109.8(56)
Zn1−N2	2.489(7)	O1−O2−H21	112.0(81)
Zn1−N3	2.029(6)	H11−O1−H1	103.0(99)
Zn1−N16	2.308(7)	H21−O2−H1	128.3(99)
Zn2−O2	1.871(6)	O1−Zn1−N1	125.8(3)
Zn2−N10	2.020(7)	O1−Zn1−N2	89.0(3)
Zn2−N11	2.032(6)	O1−Zn1−N3	131.4(3)
Zn2−N12	2.308(7)	O1−Zn1−N16	91.7(2)
Zn2−N9	2.466(7)	N1−Zn1−N2	87.0(2)
O1···O2	2.418(9)	N1−Zn1−N3	101.0(3)
Zn1···O2	3.833(7)	N1−Zn1−N16	100.7(2)
Zn2···O1	3.832(6)	N2−Zn1−N3	80.1(2)
Zn1···Zn2	5.034(1)	N2−Zn1−N16	169.9(2)
O1−H1	1.20(14)	N3−Zn1−N16	91.9(2)
O1−H11	0.73(12)	O2−Zn2−N10	133.0(3)
O2−H1	1.34(14)	O2−Zn2−N11	123.4(3)
O2−H21	0.62(8)	O2−Zn2−N12	97.7(3)
O1−N18	2.853(10)	O2−Zn2−N9	88.0(3)
O2−N8	2.855(10)	N10−Zn2−N11	103.6(3)
Zn1−O1−O2	125.4(4)	N10−Zn2−N12	81.7(3)
Zn2−O2−O1	126.2(4)	N10−Zn2−N9	86.7(3)
Zn1−O1−H11	130.2(97)	N11−Zn2−N12	88.4(3)
Zn1−O1−H1	120.7(60)	N11−Zn2−N9	97.2(2)
O2−O1−H11	103.8(96)	N12−Zn2−N9	168.0(2)

Due to the absence of the additional alcohol molecule in the complex core, the environment of both zinc ions in **1c** is almost identical. This involves their bond lengths and angles as well as their orientation with respect to the bridging $H_3O_2^-$ unit. Both Zn−O−O angles and both nonbonding Zn···O distances are practically identical and somewhat smaller than those in **1a** and **1b**. The O···O distance (2.42 Å) is about halfway between those of the two other complexes. The Zn-O···O-Zn arrangement is roughly gauche but has a larger dihedral angle (83°) than that in **1b**. The combined effect of these features is the occurrence of the shortest Zn···Zn distance (5.03 Å) in **1c**.

Discussion

The discovery of complexes **1a**−**c** was prompted by two problems in the chemistry of their mononuclear constituents

Tp′Zn-OH. First, the original preparation of this complex type for Tp′ = **a**[17] (without the addition of KOH) seemed erratic, producing variable yields, and the resulting Tp′Zn-OH seemed to have variable solubility properties. Second, attempts to determine the pK_a of $[Tp'Zn\text{-}OH_2]^+$ or the basicity of Tp′Zn-OH for Tp′ = **a** by potentiometric methods were plagued not only by the hydrolytic destruction of the Tp′ ligand in acidic media but also by an apparent extremely slow speed of the protonations or deprotonations, allowing the pK_a to be determined not more precisely than 7.0 ± 0.5.[38] It is now clear that the pH dependent equilibria between Tp′Zn-OH, $Tp'Zn\text{-}OH_2^+$, and compound **1a** are the reason for this seemingly complex behavior.

While we have not been able yet to assess the equilibria quantitatively, we could optimize the preparative procedures by varying the amount of KOH added to the reaction mixtures. In the absence of KOH, complexes **1** are initially formed in solution and undergo a very slow conversion to Tp′Zn-OH accompanied by partial decomposition, which only for Tp′ = **a** allows the isolation of Tp′Zn-OH in appreciable quantities. One-half equivalent of KOH per equivalent of zinc leads to good yields of complexes **1**, which must not be kept in solution for too long. A full equivalent of KOH makes the conversions proceed to complexes Tp′Zn-OH but in a slow reaction. In all cases, complexes **1** seem to be reaction intermediates, and the Zn-OH_2 functions being deprotonated originate from the reagent $Zn(ClO_4)_2 \cdot 6H_2O$.

The solutions from which the complexes **1** crystallize are approximately neutral. This goes along with the above-mentioned pK_a determinations and allows the interpretation that in the given solvent mixture (methanol/dichloromethane) the compounds $Tp'Zn\text{-}OH_2^+$ have a pK_a value near 7 (i.e., 50% deprotonated at pH = 7). The favorable circumstances prevailing for the Tp′Zn ligand environments then allow the statistical situation to be turned into a stoichiometric situation. In this situation, the combination of a Zn-OH unit and a $Zn\text{-}OH_2^+$ unit as a hydrogen bridged $[Zn\text{-}OH\text{-}H\cdots OH\text{-}Zn]^+$ complex cation is stabilized by encapsulation in the ligand sphere.

The bridging $H_3O_2^-$ ligand in complexes **1** is a hydrated OH^- ion. This exists as such or in a more hydrated form in basic aqueous solutions.[39] In the crystalline state, it has been observed in a weakly hydrated form in $Na_2(NEt_3Me)[Cr\{PhC(S){=}N(O)\}_3] \cdot 0.5\ NaH_3O_2 \cdot 18H_2O$ with an O···O distance of 2.29 Å.[40] Ab initio MO calculations for the free $H_3O_2^-$ ion assign to it an O···O distance of 2.46 Å and an H−O−O−H dihedral angle of 125°.[41] In coordination chemistry, the first and a whole series of complexes with bridging $O_2H_3^-$ ligands were found by Bino,[42] and recent examples include iron and ruthenium complexes.[43,44] The O···O distances in those dinuclear complexes span the range from 2.4 to 2.6 Å.

If considered metal-free, the $H_3O_2^-$ anion of complexes **1** can be compared to some simple and isoelectronic inorganic species. The closest ones of this type are the FHF^- anion and the $H_3F_2^+$ cation. The former crystallizes as KHF_2 with a F···F distance of 2.27 Å,[45] and the latter crystallizes as $H_3F_2^+Sb_2F_{11}^-$ with a F···F distance of 2.30 Å.[46] The metalated $H_3O_2^-$ ion can also be compared to the protonated one (i.e., the $H_5O_2^+$ ion). The latter has been isolated in the form of several salts with O···O distances between 2.40 and 2.45 Å.[47] A similar bridging situation as in **1** with tricoordinate oxygen is also present in crystalline hypofluoric acid, which contains polymeric -H•[••OF-H•••]- chains with O···O distances of 2.89 Å.[48]

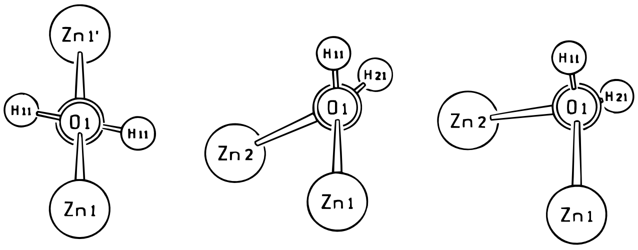

Figure 5. Projections of the $Zn\text{-}H_3O_2\text{-}Zn$ units along the O···O line for **1a** (left), **1b** (center), and **1c** (right). Dihedral angles Zn-O-O-Zn: **1a**, 180°; **1b**, 65°; **1c**, 83°.

The O···O distances between the hydrogen-bridged oxygen atoms in **1a**−**c** ranging from 2.40 to 2.45 Å represent very strong hydrogen bonds. They are at the short end of the range of such bonds in $H_3O_2^-$ bridged metal complexes,[42] and they compare well with the free $H_3O_2^-$ ion[41] or the salts of the $H_5O_2^+$ ion.[47] It can be stated that the 2-fold metal coordination relieves some of the repulsive O···O interactions due to the negative charge in the O-H···O units, just as the extensive hydrogen bonding interactions do in the hydrated NaH_3O_2 salt.[40] The comparison of the two O-H···O bridges in **1b** (intracore O1-H···O2 = 2.45 Å, extracore O2-H···O7 = 2.69 Å) can serve as an independent measure for the strength of the central O1-H···O2 bridge.

The attachment of the two metal ions to the bridging $H_3O_2^-$ ligand in the three complexes **1** varies considerably. Figure 5 displays this as Newman projections along the O···O lines. If one views the oxygen atoms as tetrahedral entities (with the unshared electron pair occupying the fourth coordination site), one can envisage gauche or anti positions of the two zinc ions. Complex **1a** represents the ideal anti situation, while **1b** and **1c** approximate the gauche situation with dihedral angles of 65 and 83°, respectively. The hydrogen atom positions also group **1b** and **1c** together where they are both involved in hydrogen bridging, while in **1a** there is no such restraint on the Zn−O−H torsion angle.

The conformations of the Zn-O-O-Zn or ZnHO-OHZn units in complexes **1** may also be compared to those of H_2O_2 or N_2H_4. The latter have dihedral angles of 112 and 95°, respectively,[47] making them closer relatives of **1b** and **1c** than of **1a**. The Zn···Zn distance in complexes **1** is, to the first approximation, a function of the dihedral angle of Zn-O···O-Zn. Accordingly, it is longest in **1a** (5.76 Å). It is shortest in **1c** (5.03 Å), although **1c** does not have the smallest dihedral angle. In **1b**, which has the smallest dihedral angle, the longer Zn···Zn distance (5.12 Å) is caused mainly by the larger Zn−O−O angles in a conformational range where a variation of the dihedral angle is of little effect.

In comparison to the trimetal enzymes alkaline phosphatase, phospholipase C, and P1 nuclease, the zinc complexes **1** can

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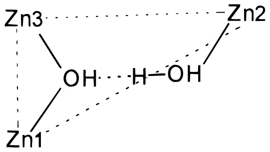

Figure 6. Representation of the attachment of Zn2 to Zn1 and Zn3 in phospholipase C and P1 nuclease in terms of the Zn-H_3O_2-Zn linking and the Zn···Zn distances in complexes **1a**−**c**.

reproduce both the 4.7 Å as well as the 5.8 Å Zn···Zn interaction. In both cases, this interaction can be described as a Zn-OH-H···OH-Zn linkage, although this has not expressly been stated for the enzyme structures. In the enzymes, the OH^- part of this linkage is bound to two zinc ions, (cf. Figure 1). Of these, Zn1 occupies an anti position with respect to the Zn2-OH_2-OH sequence, while Zn3 finds itself in a syn or gauche position with respect to the same sequence. Accordingly, the Zn1···Zn2 distance of 5.8 Å in the enzymes can be related to that of 5.8 Å in anti-configured **1a** and the Zn2···Zn3 distance of 4.7 Å in the enzymes can be related to those of 5.1 and 5.0 Å in gauche-configured **1b** and **1c**. Figure 6 depicts this as a simplified variation of Figure 1. In the enzymes, all three zinc ions are five-coordinate as are those in **1b** and **1c**. However, four-coordinate zinc is equally typical for enzymes,[1−4] and hence, **1a** is an equally viable structural model.

In the enzymes, encapsulation is the typical situation for the functional units such as Zn-OH_2 or Zn-OH whose acidity or nucleophilicity depends largely on their immediate environment. Complexes **1a**−**c** also reproduce this. In **1a**, the environment of the Zn-OH-H···OH-Zn unit is completely hydrophobic, consisting only of the cumyl substituents. In **1c**, the pyridyl substituents add a hydrophilic component and the donor capacity which increases the coordination number of the zinc ions. In **1b**, finally, a typical aspect of a hydrophilic neighborhood is visualized by the incorporation of the hydrogen-bonded methanol molecule between one Zn-OH function and one pyridyl nitrogen. Thus, in all three cases the encapsulation means protection of the functional units as well as individual tuning of a possible reactivity.

For complexes **1a**−**c**, the probing of the reactivity of the zinc-bound OH_2 or OH^- functions is hampered by their conversion to the mononuclear Tp′Zn-OH complexes in solution. In the enzymes, this cannot happen. Accordingly, the presence of three metal ions in the active center may be necessary not only for structural reasons but also for the polymetallic activation of substrates. It may also provide a variation in the activation of metal-bound water molecules for hydrolytic reactions. Along these lines, it can be proposed that the Zn-OH-H···OH-Zn unit is not only a structural but also a functional entity in hydrolytic enzymes with two or three metal ions.

Conclusion

The three tris(pyrazolyl)borate complexes **1a**−**c** containing the hydrated hydroxide ion $H_3O_2^-$ as a bridging ligand $[OH\text{-}H\cdots OH]^-$ between two zinc ions represent a new class of zinc−aqua complexes. The existence and stability of the complexes is likely to be due to the complete encapsulation of the Zn-O_2H_3-Zn unit by the voluminous aromatic substituents of the pyrazolylborate ligands. In the complexes, zinc displays its structural flexibility by adopting different coordination numbers, different Zn-O-O-Zn orientations, and, in one case, the attachment of a solvent molecule via a hydrogen bridge to the Zn-OH function. The variable Zn−O−O−Zn dihedral angles (180, 83, and 65°) allow a considerable variation of the Zn···Zn distances (5.76, 5.12, and 5.03 Å). This and the bridging $H_3O_2^-$ ligands make complexes **1a**−**c** structural models of oligozinc enzymes like phospholipase C and P1 nuclease.

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Supporting Information Available: ORTEP plots and listings of crystal data, positional parameters, bond distances and angles, anisotropic thermal parameters, calculated hydrogen atom positions for all three structures (11 pages). See any current masthead page for ordering and Internet access instructions.

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