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Equilibrium and spectroscopic studies of diethyltin(IV) complexes formed with hydroxymono- and di-carboxylic acids and their thioanalogues †

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The complex formation of diethyltin(IV) cation with glycolic (GA), lactic (LA), succinic (SA), malic (MA), tartaric (TA), mercaptoacetic (MAA), 2-mercaptopropionic (MPA), mercaptosuccinic (MSA) and dimercaptosuccinic acid (DMSA) has been investigated by potentiometric, spectrophotometric, ^{1}H NMR and Mössbauer spectroscopic methods. The mercaptocarboxylic acids yielded much more stable complexes than the corresponding hydroxy acids. Below pH 3, the carboxylate and the still protonated hydroxyl group of hydroxy acids are co-ordinated to the metal ion, while in the case of their thio analogues, {COO^-, S^-} co-ordinated species are dominant. With increasing pH, the metal promoted deprotonation of the hydroxyl group takes place in the presence of MA. In the neutral pH range, among the hydroxy acids, only MA and TA are able to suppress the formation of hydrolytic species of diethyltin(IV). Although metal co-ordinated water deprotonation was observed around pH 6–7, in the case of the mercaptocarboxylic acids, only ligand-containing complexes were formed in the whole pH range studied. Complexes displaying slow ligand exchange were detected in the case of MA and all mercaptocarboxylic acids, which allowed their structural characterization, by ^{1}H NMR spectroscopy. In agreement with the Mössbauer spectroscopic data, trigonal bipyramidal, {COO^-, O^-/S^-, OH^-} co-ordinated complexes are dominant around pH 7, with the exception of the octahedral geometry found in the dimer complex M_2L_2 of DMSA, having a {$2COO^-$, $2S^-$} donor set.

Introduction

Organotin(IV) compounds have wide-ranging practical applications, although their usage has considerably decreased in the last decade due to environmental considerations. These compounds accumulate in the environment, where they interact with living organisms by affecting various biochemical processes.[1–4] However, organotin(IV) derivatives, and particularly those of dialkyltin(IV), have been found to possess anticancer effects on different tumour cells.[5] The moieties $R_nSn(IV)^{(4-n)+}$ (n = 2 or 3) can bond to proteins and glycoproteins of the cell membranes, and also to cellular proteins and DNA, *e.g.* $Et_2Sn(IV)^{2+}$ to ATPase and hexokinase,[6] $Bu_2Sn(IV)^{2+}$ or $Bu_3Sn(IV)^+$ to ATPase and acetylcholinesterase of the human erythrocyte membrane,[7] and $Me_2Sn(IV)^{2+}$ to the phosphate group of DNA fragments.[8] In biological media, the thiol groups of cysteine residues are one of the main binding sites for organotin(IV) compounds, yielding products characterised by Sn–S bonds.[9] Carboxylate oxygens are also frequent donor atoms for organotin(IV) cations in both proteins and biologically relevant low molecular weight compounds, such as amino acids[10,11] and glutathione.[12] These facts have led to considerable efforts to characterise organotin(IV) complexes with ligands containing oxygen and/or sulfur[10–20] donor atoms. For a better understanding of the interaction of organotin(IV) compounds with biological systems, the complex formation equilibria and solution structures of alkyltin(IV) complexes with carboxylic acids,[11,16] sugars[17] and sugar derivatives,[18,19] amino acids,[10,11] peptides[12,20] and DNA fragments[8] have also been investigated.

The interaction of sulfanylcarboxylate ligands with organotin(IV) cations is interesting from the practical point of view, since such complexes are widely used as polyvinyl chloride stabilizers.[21] Thiol-containing ligands are also of great importance in the treatment of metal intoxication.[22] DMSA is known to be efficient in reducing thymus and bile duct damage in mice exposed to dibutyltin(IV), and is also an antidote in rats.[23,24] It was also successfully applied orally to treat human intoxication with trimethyltin(IV) added to a red wine with homicidal intent.[25] In spite of the great efforts to elucidate the structure of hydroxy- and thio-carboxylic acid complexes of dialkytin(IV) cations in the solid-state,[14,15,26,27] to our knowledge, no information is available on the solution properties of such compounds. The present paper describes the equilibrium properties and solution structures of diethyltin(IV) complexes formed with some simple mono- and di-hydroxycarboxylic acids and their thioanalogues. The solid-state structures of these complexes have already been reported by us.[15,26]

Experimental

Materials

Diethyltin(IV) dichloride was purchased from Alfa Aesar. The ligands used are depicted in Scheme 1. They were Merck (MA), Reanal (LA, TA), Sigma (SA, MA, MSA), Aldrich (MAA, MPA) and Fluka (DMSA) products and were used without

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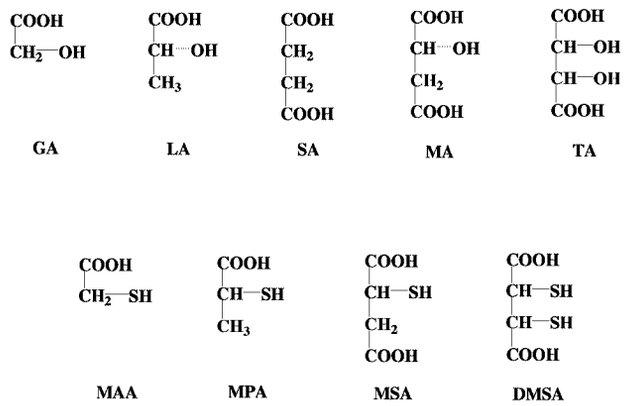

Scheme 1 Structures of the ligands studied: glycolic acid (GA); lactic acid (LA); succinic acid (SA); malic acid (MA); tartaric acid (TA); mercaptoacetic acid (MAA); 2-mercaptopropionic acid (MPA); mercaptosuccinic acid (MSA); meso-2,3-dimercaptosuccinic acid (DMSA).

further purification. The pH-metric titrations were performed with standard NaOH solution (Fluka). Other reagents and solvents were purchased from Reanal.

pH-Metric measurements

The protonation and co-ordination equilibria were investigated by potentiometric titration in aqueous solution (I = 0.1 mol dm^{-3}, $NaClO_4$, and T = 298 ± 0.1 K) in an automatic titration set including a Dosimat 665 (Metrohm) autoburette, an Orion 710A precision digital pH-meter and an IBM-compatible PC. The Orion 8103BN semimicro pH glass electrode was calibrated *via* the modified Nernst[28] equation:

$$E = E_0 + K\cdot\log[H^+] + J_H\cdot[H^+] + \frac{J_{OH}\cdot K_W}{[H^+]} \qquad (1)$$

where J_H and J_{OH} are fitting parameters in acidic and alkaline media for the correction of experimental errors, mainly due to the liquid junction and to the alkaline and acidic errors of the glass electrode; $K_w = 10^{-13.75}$ mol^2 dm^{-6} is the autoprotolysis constant of water.[29] The parameters were calculated by a non-linear least squares method. The species formed in the systems were characterised by the generalised equilibrium process:

$$pM + qL + rH \Leftrightarrow M_pL_qH_r$$

where M denotes the diethyltin(IV) cation and L the non-protonated ligand molecule. Charges are omitted for simplicity, but can be easily calculated taking into account the following notation for the fully protonated neutral ligands: GA, LA (LH); MA, SA, TA, MAA, MPA (LH_2), MSA (LH_3) and DMSA (LH_4). The formation constants of the formed complexes were calculated *via* the computer program PSEQUAD.[30]

The protonation and complex formation constants were determined from 4 and 7 independent titrations (60–90 data points per titration), respectively. The metal-to-ligand ratios varied between 1 : 1 and 1 : 8, and the diethyltin(IV) concentration ranged from 9 × 10^{-4} to 4 × 10^{-3} mol dm^{-3}. Due to its low solubility, in the case of DMSA 9 × 10^{-4} mol dm^{-3} ligand concentration (M : L = 1 : 1 to 1 : 3) and 30–40 cm^3 initial volume were used. The pH-metric data between pH 2 and 10–11 were taken into account during the evaluation. Some examples of experimental and calculated titration curves, for all studied systems, are provided in the ESI (Fig. S2–S10).

Spectrophotometric measurements

A Hewlett-Packard 8452A Diode-Array Spectrophotometer was used to determine the stability constant of the complex formed below pH 2, in the case of all diethyltin(IV)–mercaptocarboxylic acid systems. The absorption of the thiolate group was followed between 220 and 250 nm, by adding increments of 0.2 mol dm^{-3} $HClO_4$ to a solution containing the corresponding mercaptocarboxylic acid and Et_2SnCl_2. Because of the highly acidic medium, the ionic strength of the solution could not be held at 0.1 mol dm^{-3}. The measured absorption decreased with the decrease of the pH until the spectrum of the free ligand, containing protonated thiol group(s), was recovered (see Fig. S1, ESI). The collected data were processed with the PSEQUAD program to obtain the stability constants of the first-formed complexes, which were kept constant during the evaluation of the potentiometric data.

NMR measurements

^{1}H NMR measurements were performed on a Bruker Avance DRX 500 spectrometer. The chemical shifts were measured with respect to 1,4-dioxane as an internal reference and converted relative to TMS, using $\delta_{dioxane}$ = 3.70 ppm. The heteronuclear couplings $^2J_{(^{119}Sn-^1H)}$ were "converted" into C–Sn–C angles by using the published equations.[31]

For ^{1}H NMR measurements, the ligand and metal concentrations were varied in the interval 0.005–0.02 mol dm^{-3}. Measurements were generally made in a 9 : 1 H_2O : D_2O solution. In a few cases, they were performed in pure D_2O.

Mössbauer spectroscopic measurements

The ^{119}Sn Mössbauer spectra were measured in fast-frozen solution at liquid nitrogen temperature (77.3 ± 0.1 K) with a multichannel analyser [TAKES Mod. 269, Ponteranica, Bergamo (Italy)] and Wissenschaftliche Elektronik system [MWE, München (Germany)]: an MR250 driving unit, an FG2 digital function generator and an MA250 velocity transducer, moved at linear velocity, with constant acceleration, in a triangular waveform. The multichannel calibration was performed with an enriched iron foil [^{57}Fe = 95.2%, thickness 0.06 mm, Dupont, MA (USA)], at room temperature, with a ^{57}Co–Pd source [(10 mCi, Ritverc GmbH, St. Petersburg (Russia)], while the zero point of the Doppler velocity scale was determined at room temperature through the absorption spectra of natural $CaSnO_3$ (^{119}Sn = 0.5 mg cm^{-2}) and a $Ca^{119}SnO_3$ source [10 mCi, Ritverc GmbH, St. Petersburg (Russia)]. The obtained spectra of 5 × 10^5 counts were refined with appropriate software[32] to establish the isomer shift, δ (mm s^{-1}), the nuclear quadrupole splitting, Δ (mm s^{-1}), and the width at half-height of the resonant peaks, Γ (mm s^{-1}). The experimental Δ_{exp} values were compared with the calculated ones (Δ_{cal}), assuming different stereochemistries of the co-ordination sphere of tin(IV), according to the point charge model formalism.[33,34] The partial quadrupole splitting (pqs) values of the functional groups used in the calculations are listed in Table 1.

Results and discussion

Hydroxo complexes of diethyltin(IV)

Diethyltin(IV) forms stable and water-soluble mono- and binuclear hydroxo complexes in the studied pH range. The hydrolysis of this cation in aqueous solution has been studied by several groups.[18,35,36] The hydrolysis constants we determined (Table 2) are in good agreement with those already published, and are taken into consideration during the evaluation of the pH-metric data. The hydroxo complexes formed between pH 2–11.5 were also investigated by means of a pH-dependent ^{1}H NMR study and the individual NMR parameters (δ, ^2J) of the different hydrolytic species are presented in Table S1 (ESI). The C–Sn–C angles determined from the appropriate $^2J_{(^{119}Sn-^1H)}$ coupling constants[31] indicate the predominance of the trigonal bipyramidal structure in the hydrolytic species.

Table 1 Partial quadrupole splitting (pqs) values of the functional groups used in the calculations (mm s^{-1})[a]

$\{R\}^{oct} = -1.03$	$\{R\}^{tba} = -0.94$	$\{R\}^{tbe} = -1.13$	$\{R\}^{tetr} = -1.37$
$\{COO^-\}_m^{oct} = -0.135$	$\{COO^-\}_m^{tba} = -0.1$	$\{COO^-\}_m^{tbe} = 0.06$	$\{COO^-\}_m^{tetr} = 0.15$
$\{COO^-\}_b^{oct} = 0.083$	$\{COO^-\}_b^{tba} = 0.075$	$\{COO^-\}_b^{tbe} = 0.293$	$\{COO^-\}_b^{tetr} = 0.097$
$\{S^-\}^{oct} = -0.56$	$\{S^-\}^{tba} = -0.595$	$\{S^-\}^{tbe} = -0.60$	$\{S^-\}^{tetr} = -0.49$
$\{O^-\}^{oct} = -0.27$	$\{O^-\}^{tba} = -0.21$	$\{O^-\}^{tbe} = -0.09$	$\{O^-\}^{tetr} = -0.37$
$\{OH/OH^-\}^{oct} = -0.14$	$\{OH/OH^-\}^{tba} = -0.13$	$\{OH/OH^-\}^{tbe} = 0.02$	$\{OH/OH^-\}^{tetr} = -0.40$
$\{H_2O\}^{oct} = 0.20$	$\{H_2O\}^{tba} = 0.18$	$\{H_2O\}^{tbe} = 0.43$	$\{H_2O\}^{tetr} = 0.276$

[a] b: bidentate; m: monodentate; oct: octahedral geometry; tba: axial position in trigonal bipyramidal (tbp) geometry; tbe: equatorial position in trigonal bipyramidal (tbp) geometry; tetr: tetrahedral geometry.

Table 2 Formation constants and derived data for the diethyltin(IV) complexes of hydroxy- and mercapto-carboxylic acids (as their logarithms) at T = 298 K, I = 0.1 M $NaClO_4$; $\beta_{pqr} = M_pL_qH_r/[M]_p[L]_q[H]_r$ with estimated errors[a] in parentheses (last digit). The formation constants of the hydrolytic species are as follows: $\beta_{10-1} = -3.141(3)$, $\beta_{10-2} = -8.550(4)$, $\beta_{10-3} = -19.827(5)$, $\beta_{20-2} = -4.81(3)$, $\beta_{20-3} = -9.98(2)$

pqr	GA	LA	SA	MA	TA	MAA	MPA	MSA	DMSA
011	3.64(1)	3.69(1)	5.24(1)	4.74(1)	3.92(1)	9.90(1)	10.17(1)	10.34(1)	11.6(2)
012	—	—	9.24(1)	8.02(1)	6.81(1)	13.37(1)	13.72(1)	14.93(1)	21.11(1)
013	—	—	—	—	—	—	—	18.08(1)	24.57(1)
014	—	—	—	—	—	—	—	—	26.98(1)
112	—	—	—	—	—	—	—	—	29.07(7)[b]
111	—	—	8.51(3)	7.69(4)	6.40(6)	—	—	18.47(8)[b]	26.11(2)
110	3.05(8)	2.90(6)	4.65(2)	5.09(2)	4.33(1)	14.16(6)[b]	14.13(3)[b]	14.18(1)	—
220	—	—	—	—	—	—	—	—	43.41(5)
11−1	−0.12(5)	−0.09(2)	−0.27(2)	1.51(2)	0.90(1)	7.64(2)	7.48(3)	7.24(1)	—
11−2	—	—	—	−6.30(4)	−5.83(3)	—	—	—	—
22−1	—	—	—	—	—	—	—	—	33.11(6)
$\log K_{M+LH_x}$[c]	3.05	2.90	3.27	2.95	2.49	13.85	14.13	13.88	—
$\log K_{ML}^{corr}$[d]	—	—	−4.59	−2.93	−2.48	—	—	—	—
pK_{ML}	3.17	2.99	4.92	3.58	3.43	6.52	6.65	6.94	10.3[e]
$pK_{MLH_{-1}}$	—	—	—	7.81	6.73	—	—	—	—
NP	318	389	345	402	381	350	410	342	347
FP	0.01	0.007	0.006	0.008	0.007	0.008	0.008	0.009	0.006

[a] Twice the standard deviation, or 0.01 if 2 × STD < 0.01. [b] Obtained spectrophotometrically, during these measurements the ionic strength could not be held constant (I = 0.1–0.2 M). [c] $M + LH_x = MLH_x$ where $x = 0$ (GA, LA, MAA and MPA), $x = 1$ (SA, MA, TA and MSA), in the case of MSA the remote carboxylate group is considered to be protonated. [d] $M + LH_2 = ML + 2H$. [e] $pK_{M_2L_2}$; NP number of experimental points; FP fitting parameter (cm^3).

Complex formation with mono- and di-hydroxycarboxylic acids

The determined protonation and stability constants, together with some calculated data, are presented in Table 2. The listed protonation constants agree well with those obtained earlier under the same conditions we used.[11,37,38]

The values given in Table 2 for $\log K_{M+LH_x}$ (where $x = 0$ for GA and LA, $x = 1$ for SA, MA and TA) agree well with each other, taking into account the different acidity of the ligands. This suggests identical, monodentate carboxylate co-ordination in these complexes, and does not show additional co-ordination of the OH group(s) in the hydroxy dicarboxylic acids as compared with SA. The additional stabilisation of the hydroxy group(s), however, can be seen clearly from the basicity-corrected stability constants of the complexes ML ($\log K_{ML}^{corr}$). $\log K_{ML}^{corr}$ is nearly two orders of magnitude lower in case of SA than those of MA and TA. This difference can only be attributed to the additional co-ordination (and consequently stabilisation) of the OH group(s). In other words, the seven-membered chelate ring, formed in the case of SA as ligand, is much less stable than the fused chelate rings of MA and TA, formed with the participation of still protonated OH group(s).

The presence (or absence) of the OH groups governs the successive deprotonation processes, too. The pK values for the reaction $ML = MLH_{-1} + H^+$ is much higher for SA than for the OH-containing diacids (Table 2). This suggests that different donor groups are involved in these processes. In the case of SA, where no additional deprotonating group is available, a mixed-hydroxo species (ML(OH)) is formed. The considerably lower pK values in the case of MA and TA may indicate metal-promoted deprotonation of hydroxyl groups, *i.e.* formation of the complexes MLH_{-1}.

During the successive deprotonation processes, our potentiometric data indicate the decomposition of the diethyltin(IV)-ligand complexes in the cases of SA, GA and LA, yielding the very stable hydrolytic species $M(OH)_2$. For MA and TA the pK values of this second deprotonation ($pK_{MLH_{-1}}$ = 7.81 and 6.73 for MA and TA, respectively) are much higher than that of the species M(OH) (pK = 5.41), thus the additional donor group(s) prevent(s) the formation of $M(OH)_2$, and ligand-containing complexes are also present throughout the whole pH range (Fig. 1A). The observed deprotonation in the MA and TA containing systems can be attributed to three different processes, which result in three different species $ML(OH)_2$, $MLH_{-1}(OH)$ or MLH_{-2}. In order to distinguish among these possibilities and to obtain structural information on the complexes formed, ^{1}H NMR and Mössbauer measurements were performed.

Representative ^{1}H NMR spectra for the MA and SA containing systems are shown in Fig. 2 and S11 (ESI), respectively. Around pH = 3 (MA) and 4.5 (SA) the $(Et)_2SnL$ complexes are dominant in the solutions (Fig. 1A). In both cases the ethyl protons of the metal ion are shifted upon complex formation. At the same time, the ligand protons are slightly affected, only line broadening can be observed. This is selective for one of the inequivalent CH_2 protons in the case of MA (Fig. 2b), suggesting chelated {COO^-, OH} co-ordination of the ligand, with the participation of the non-deprotonated hydroxyl group, as already proposed on the grounds of pH-metric results.

The ^{1}H NMR spectra of the SA containing system (Fig. S11, ESI) is slightly affected by the successive deprotonation, which is in agreement with the formation of the complex ML(OH). However, a new set of signals appeared above pH 4 in the case of MA (Fig. 2d), parallel with the formation of the complex MLH_{-1}, indicating slow ligand exchange for this species,

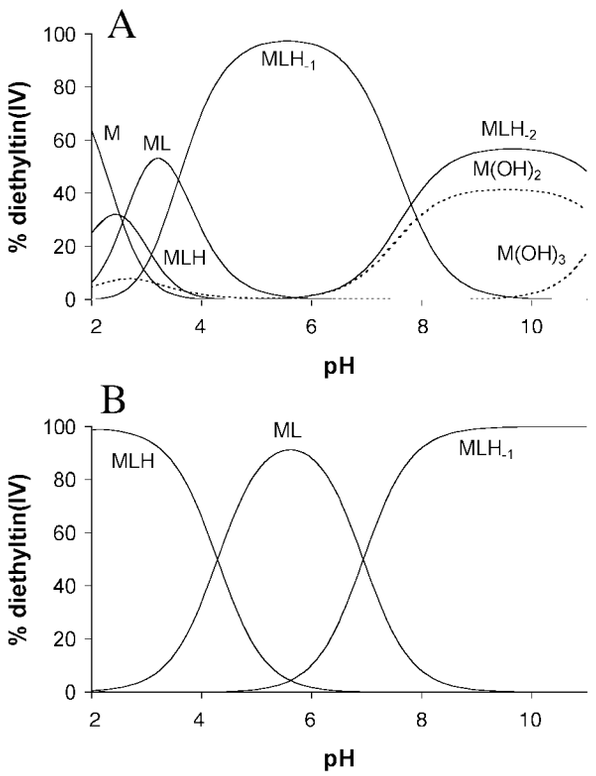

Fig. 1 Species distribution curves of the diethyltin(IV)–MA (A) and –MSA (B) systems (2.5[M] = [L] = 0.01 mol dm^{-3}). Hydrolytic species are shown by dashed lines.

relative to the NMR time scale. The ratio of the bound and unbound ligand signals indicates nearly 100% formation of the complex MLH_{-1}, in agreement with its speciation curve in Fig. 1A. The CH and CH_2 protons in MLH_{-1} are downfield shifted by 0.25 and 0.15 ppm, respectively, as compared with the free ligand (Table 3). The formation of the slow exchanging complex itself and the higher shift of the CH proton indicate the deprotonation of the hydroxyl group during the process ML = $MLH_{-1} + H^+$, forming a $\{COO^-, O^-\}$ co-ordinated complex in the case of MA.

The ethyl signals of the organotin moiety in the complexes MLH_{-1} (or ML(OH)) of the other ligands (GA, LA and TA) confirm the proposed speciation, but the ligand signals do not show characteristic differences as compared with the metal-free systems. This suggests hydrolytic process, *i.e.* the formation of hydroxo-mixed complexes, during the deprotonation in question. However, in spite of the ^{1}H NMR results, the potentiometric data in the case of TA indicate an analogous process to that mentioned above for MA. A possible reason for this contradiction is that the chemical shift of the CH protons is close to the water signal, which would result in overlapped peaks of the possibly formed slow exchanging complex and the solvent. In agreement with this hypothesis, the observed intensity of the CH protons, is lower as expected for a fast ligand exchanging complex.[39] Nevertheless, the formation of hydroxo-mixed complexes of TA can not be ruled out.

Although the relative simplicity of the species distribution of these systems made it possible to determine the structures of some dominant species by means of Mössbauer spectroscopic study on fast-frozen solutions, in a few cases precipitation occurred at the concentrations necessary for the measurements. The experimental results obtained for the MLH_{-1} complexes are shown in Table 4. The pqs calculations were performed for all possible stereoisomers of tetrahedral, trigonal bipyramidal (tbp) and octahedral (oct) cases. Only a few co-ordination geometries were found to be in agreement with all experimental (potentiometric, ^{1}H NMR and Mössbauer spectroscopic) results. For GA and TA, the experimental data do not allow the distinction of three very similar tbp structures (Fig. 3, tbp1–3), containing either alkoxo group or hydroxide ion as ligand. The considerably higher Δ_{exp} value obtained for the MLH_{-1} complex of MA suggests a tbp structure, too, but the ethyl groups are likely to be in *trans* position (tbp4).

Above pH 8, only MA and TA are able to suppress the hydrolysis of diethyltin(IV). The deprotonation of the MLH_{-1} complex of MA (pK = 7.81) stops the slow ligand exchange, thus only some line broadening and the shift of the ethyl ^{1}H NMR signals reveal the presence of ligand containing complex (Fig. 2f). This indicates rearrangement of the co-ordination sphere, *i.e.* in parallel with reprotonation of the alkoxo group, two metal-co-ordinated water deprotonations take place, forming the complex $ML(OH)_2$. The analogous process occurs at

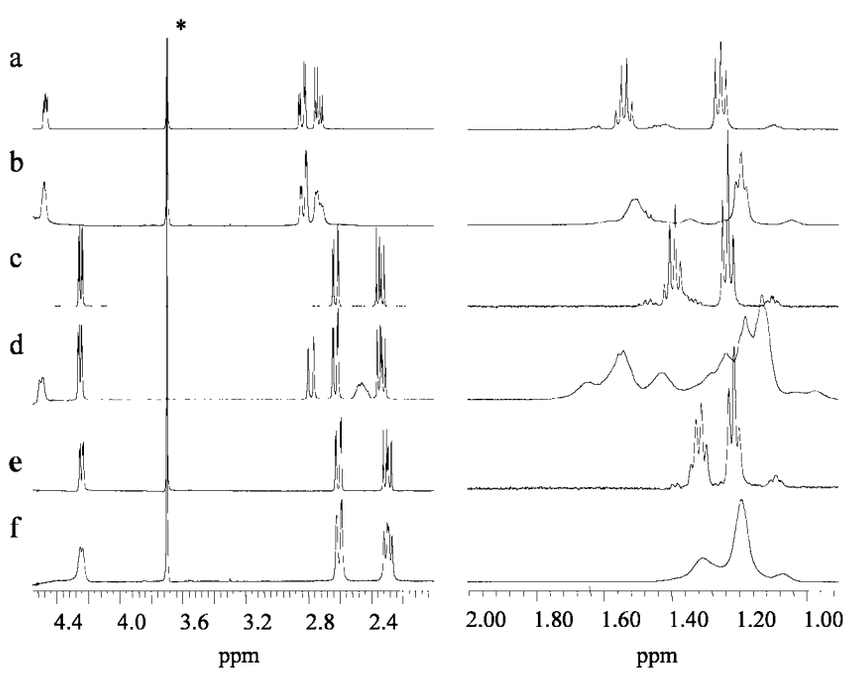

Fig. 2 Part of the ^{1}H NMR spectra of the diethyltin(IV)–MA 1 : 2.5 system (b, d, f) and of the free ligand and the free metal (a, c, e), respectively. pH = 3.0 (a, b), 5.5 (c, d), 9.8 (e, f). 2.5[M] = [L] = 0.01 mol dm^{-3}. The asterisk denotes the dioxane signal.

Table 3 ^{1}H NMR chemical shifts in ppm and coupling constants in Hz (in parentheses) for slow ligand exchanging complexes with diethyltin(IV) in aqueous solution at different pH. [L] = 0.01 mol dm^{-3}

Species	δ_{CH}	δ_{CH_2}	δ_{CH_3}	δ_{CH_2}(Et$_2$Sn(IV))	δ_{CH_3}(Et$_2$Sn(IV))
Et$_2$Sn(IV)/MA MLH$_{-1}$; pH = 5.5	4.50	2.77, 2.43[a]	—	1.54[b]	1.18[b]
	(^3J = 9.7)	(^2J = 17.7)	—	—	—
Free L and free M	4.25	2.63, 2.34[a]	—	1.39	1.23
	(^3J = 9.7)	(^2J = 15.2)	—	(^3J = 7.9)	(^3J = 7.9)
Et$_2$Sn(IV)/MAA ML; pH = 3.5	—	3.44[b]	—	1.47	1.24
	—	—	—	($^3J_{H-H}$ = 7.9; $^2J_{Sn-H}$ = 62 Hz)	(^3J = 7.9)
Free L and free M	—	3.26	—	1.51	1.25
	—	—	—	(^3J = 7.9)	(^3J = 7.9)
Et$_2$Sn(IV)/MAA MLH$_{-1}$; pH = 8.5	—	3.28[b]	—	1.31[b]	1.21
	—	—	—	—	(^3J = 6.7)
Free L and free M	—	3.13[b]	—	1.32	1.21
	—	—	—	(^3J = 7.3)	(^3J = 7.3)
Et$_2$Sn(IV)/MPA ML; pH = 3.5	3.80[b]	—	1.42[b]	1.46[b]	1.24
	—	—	—	—	(^3J = 7.9)
Free L and free M	3.55	—	1.42	1.51	1.25
	(^3J = 6.7)	—	(^3J = 6.7)	(^3J = 7.9)	(^3J = 7.9)
Et$_2$Sn(IV)/MPA MLH$_{-1}$; pH = 8.5	3.63[b]	—	1.38	Overlapped	1.22[b]
	—	—	(^3J = 6.7)	—	—
Free L and free M	3.42	—	1.37	1.32	1.21
	(^3J = 6.7)	—	(^3J = 6.7)	(^3J = 7.3)	(^3J = 7.3)
Et$_2$Sn(IV)/MSA MLH$_{-1}$; pH = 8.6	3.91[b]	2.85, 2.28[a]	—	Overlapped	1.22[b]
	—	(^2J = 14.6)	—	—	—
Free L and free M	3.56	2.76, 2.37[a]	—	1.32	1.21
	(^3J = 5.5)	(^2J = 15.2)	—	(^3J = 7.3)	(^3J = 7.3)
Et$_2$Sn(IV)/DMSA M$_2$L$_2$; pH = 7.7	4.18	—	—	≈1.45[b]	1.26
	—	—	—	—	(^3J = 8.1)
Free L and free M	3.26	—	—	1.32	1.21
	—	—	—	(^3J = 7.9)	(^3J = 7.9)

[a] AB case. [b] Broad signal.

Table 4 Mössbauer parameters (in mm s^{-1}) for complexes of diethyltin(IV) with some hydroxy- and mercapto-carboxylic acids at selected pH

Ligand	M : L	pH	Species	IS	$\lvert\Delta_{exp}\rvert$	$\lvert\Delta_{cal}\rvert$	Structure (see Fig. 3)
GA	1 : 6	5.0	MLH$_{-1}$	1.20	3.04	2.95–3.11	tbp1–3
MA	1 : 2	6.0	MLH$_{-1}$	1.39	3.91	4.23	tbp4
TA	1 : 2	5.2	MLH$_{-1}$	1.33	3.27	2.95–3.11	tbp1–3
MAA	1 : 1	8.5	MLH$_{-1}$	1.31	2.65	2.57	tbp5
	1 : 2	8.5	MLH$_{-1}$	1.41	2.68	2.57	tbp5
MPA	1 : 1	8.5	MLH$_{-1}$	1.39	2.58	2.57	tbp5
	1 : 2	8.5	MLH$_{-1}$	1.41	2.63	2.57	tbp5
MSA	1 : 1	5.8	ML	1.40	3.15	3.15	tbp6
	1 : 1	10.4	MLH$_{-1}$	1.28	2.63	2.57	tbp5
	1 : 2	9.0	MLH$_{-1}$	1.44	2.62	2.57	tbp5
DMSA	1 : 2	4.5	MLH	1.45	4.12	3.97	tbp7
	1 : 2	9.5	M$_2$L$_2$	1.47	2.65	2.70	oct1

much lower pH in the case of TA (pK = 6.73), but due to the difficulties mentioned above for the MLH$_{-1}$ complex of TA, no definite conclusion can be made concerning the co-ordination mode of this ligand.

Complex formation of mono- and di-mercaptocarboxylic acids

The SH-containing ligands offer much more stable metal-binding sites to the organotin(IV) cation than the OH-carboxylic acids do, suppressing completely the hydrolysis of diethyltin(IV). The high stability of the complexes results in a low concentration of the free metal ion in the acidic region of the pH-metric titration curves, which hindered the evaluation of potentiometric data. Therefore, the stability constants of the complexes formed below pH 2 were determined by spectrophotometric methods. During these measurements the ionic strength could not be held constant (see also the Experimental section). The spectra recorded in the diethyltin(IV)–MPA system are presented in Fig. S1 (ESI), as an example of the spectral change and the goodness of the fit.

The similar log $K_{M + LH_x}$ values for the reaction M + LH$_x$ = MLH$_x$ (where x = 0 for MAA and MPA, x = 1 for MSA) collected in Table 2 again suggest an identical co-ordination mode in the first-formed complexes. Since two protons are liberated by the metal ion at pH 2 in all discussed systems, in the first-formed complexes bidentate {COO$^-$, S$^-$} co-ordination is likely to form, which is in agreement with the high log $K_{M + LH_x}$ values. The pK values for the processes MLH = ML + H$^+$ (MSA, 4.29) and MLH$_2$ = MLH + H$^+$ (DMSA, 2.96) are close to the pK of the second carboxyl group of the free ligands (4.59 and 3.46). This suggests that the second (more remote) carboxylate group is weakly co-ordinated, if at all. The pK of the next deprotonation step in the case of DMSA (MLH = ML + H$^+$) takes place around pH 6, which is much lower than the corresponding pK of the free ligand (11.6). This deprotonation can be ascribed either to the metal-promoted deprotonation of the second thiol group or to that of the co-ordinated water molecule. However, with regard to the extremely high affinity of the organotin(IV) cation for sulfur donor atoms, the metal co-ordination of both thiolates of DMSA is more likely. This is also supported by our NMR data (see later). Simple metal ions generally form dimer complexes with DMSA.[38] Taking into account the co-ordination of both thiolate groups, our Mössbauer study (see later) also suggests the dimerization, and thus the complex

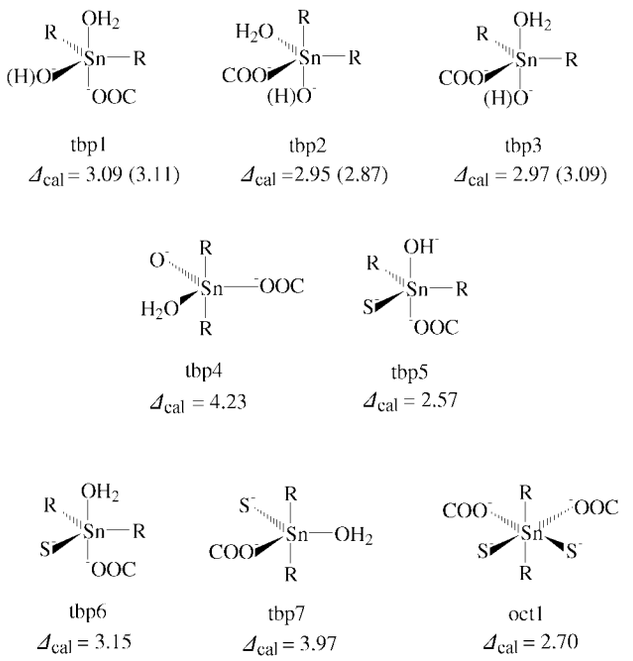

Fig. 3 Proposed local environments of diethyltin(IV) within the complexes formed with hydroxy- and mercapto-carboxylic acids, as suggested by Mössbauer and other spectroscopic measurements. In all cases monodentate carboxylate groups were considered.

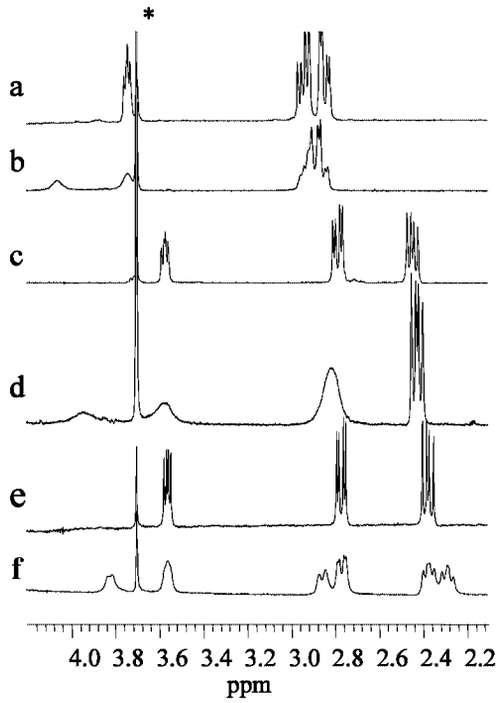

Fig. 4 Part of the ^{1}H NMR spectra of the diethyltin(IV)–MSA 1 : 2.5 system (b, d, f) and of the free ligand (a, c, e). pH = 2.6 (a, b), 5.5 (c, d) and 8.6 (e, f). 2.5[M] = [L] = 0.01 mol dm^{-3}. The asterisk denotes the dioxane signal.

M_2L_2 has been considered during our calculations instead of its mononuclear analogue (ML).

The ML complexes formed in the case of MAA, MPA and MSA, undergo a co-ordinated water deprotonation around pH 6.5–7, forming the complex ML(OH), which is the only species up to pH 10–11. The formation of similar hydroxo mixed complexes with DMSA is considerably shifted to the higher pH region (pK = 10.3), due to the very stable {2COO$^-$, 2S$^-$} co-ordination in M_2L_2.

In contrast to the hydroxy acids, the ^{1}H NMR spectra of their thio analogues display the formation of slow exchanging complexes in the whole pH range studied. The spectra of the diethyltin(IV)–monocarboxylic acid (MAA, MPA) systems, recorded at three fold ligand excess and at pH 3.5, confirm the 100% formation of the species ML, already suggested by the speciation study. The significant downfield shift of the bound CH signals (0.2 and 0.28 ppm for MAA and MPA, respectively) as compared to the free ligands, points to the co-ordination of the deprotonated thiol group beside the carboxylate. The $^2J_{Sn-H}$ coupling constant could be determined only for the MAA complex ($^2J_{Sn-H}$ = 62 Hz) which corresponds[31] to a C–Sn–C angle of *ca.* 114°, suggesting a trigonal bipyramidal structure around the metal ion. All signals of the spectra are upfield shifted during the deprotonation of the metal-bound water molecule (ML = ML(OH) + H$^+$, see Table 3). The Mössbauer parameter Δ_{exp} determined for this hydroxo mixed-ligand complex (Table 4) suggests a trigonal bipyramidal geometry with the two ethyl and the thiolate groups in the equatorial plane (Fig. 3, tbp5).

Slow ligand exchange, on the NMR time scale, was detected for the first-formed MLH complex of MSA, too (Fig. 4b). During its deprotonation (MLH = ML + H$^+$) a continuous shift of both the bound and unbound signals was observed, suggesting, that the remote carboxylate does not co-ordinate to the metal ion in the complex ML. The CH signal of the bound ligand in both MLH and ML underwent a significant downfield shift (≈0.4 ppm), as compared to the free ligand (Table 3), which confirm the co-ordination of the thiolate in the above mentioned two complexes. Both the coupling constant of tin with the methyl protons ($^2J_{Sn-H}$ = 63 Hz, ∠C–Sn–C ≈ 115°) and the Mössbauer parameter Δ_{exp} determined for the complex ML, indicate trigonal bypiramidal geometry around the metal ion, with an axially co-ordinated carboxylate group and water molecule (Fig. 3, tbp6). The deprotonation of this water molecule (ML = ML(OH) + H$^+$) results in well separated bound and unbound CH_2 signals, too (Fig. 4d). The Δ_{exp} value measured for the complex ML(OH) suggests an identical co-ordination geometry as mentioned for the analogous species of MAA and MPA (Fig. 3, tbp5).

The rather low solubility (< 1mM) of DMSA and its protonated complexes (MLH_2, MLH) hindered the spectroscopic study of this system up to pH 7, but the complex M_2L_2 has sufficient solubility, even for the Mössbauer measurements. At pH 7.7, the CH protons of DMSA are 0.9 ppm downfield shifted as compared with the free ligand (Fig. 5). This displacement is 2–4 fold higher than observed in the analogous ML complexes of MAA, MPA or MSA, and thus suggests the deprotonation and metal co-ordination of both thiol groups. Taking into account the ligand structure, the ^{1}H NMR and Mössbauer spectroscopic data (Δ_{exp} = 2.65) suggest an octahedral structure for the complex M_2L_2 with axial positions for the ethyl groups (Fig. 3, oct1).

Conclusions

Combined potentiometric, spectrophotometric and spectroscopic (^{1}H NMR, Mössbauer) measurements were used to characterise the complexes formed in the diethyltin(IV)–hydroxy- and mercapto-carboxylic acids systems. Our data clearly reveal that the mercaptocarboxylic acids form much more stable complexes with diethyltin(IV) in aqueous solution than the analogous hydroxycarboxylic acids do. In contrast to the solid complexes,[15,26] where cyclic oligomers and linear polymers are formed, in aqueous solution only mononuclear complexes with trigonal bypyramidal geometry have been found, with the exception of the {2COO$^-$, 2S$^-$} co-ordinated dimer (M_2L_2) species of DMSA.

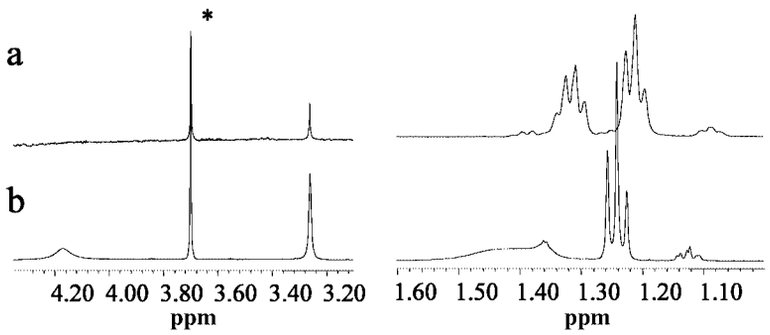

Fig. 5 Part of the ^{1}H NMR spectra of the diethyltin(IV)–DMSA system (b) and of the free ligand and the free metal (a), respectively. pH = 7.7, 2[M] = [L] = 0.01 mol dm^{-3}. The asterisk denotes the dioxane signal.

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