Synthesis, spectroscopic (Mössbauer, IR and NMR) and X-ray structural studies of diorganotin complexes of 2,2'-bipyrimidine and further NMR studies of diorganotin-pyrazine and −2,2'-azopyridine complexes

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Abstract

The ligand 2,2'-bipyrimidine (bipym) was reacted with diorganotins R_2SnCl_2 (R = methyl, ethyl) and complexes of the types R_2SnCl_2bipym, R_2SnCl_2bipym · bipym and $(R_2SnCl_2)_2$bipym were synthesized and studied by ^1H and ^{13}C NMR spectroscopy in solution, and by IR and Mössbauer spectroscopy in the solid state and frozen solutions. The complexes Et_2SnCl_2bipym · bipym and $(Et_2SnCl_2)_2$bipym were characterized by X-ray diffraction methods. In both complexes the tin environment is octahedral with chloro atoms in a cis disposition, the ethyl groups in a trans disposition and two N atoms from the ligand bipym. The second complex is a centrosymmetric binuclear species that has the ligand lone-pairs bound to two Et_2SnCl_2 units, whereas the first has one Et_2SnCl_2 species bound to the ligand and one ligand uncoordinated. The data obtained by ^{119}Sn Mössbauer spectroscopy for the solids and for frozen solutions indicate the presence of quadrivalent tin in an octahedral environment with trans alkyl groups, in keeping with the X-ray structures. The NMR spectra, however, reveal ligand lability in solution, and the C–Sn–C angles calculated from coupling constants suggest a coordination number of between 5 and 6. These results together with the long Sn–N bond distances in crystals of Et_2SnCl_2bipym · bipym and $(Et_2SnCl_2)_2$bipym suggest that these complexes may have a potential antitumour activity.

Keywords: Organotin; Bipyrimidine; Mössbauer spectra; Crystal structure; NMR; Nitrogen bases

1. Introduction

Cancer chemotherapy commonly involves the use of organic compounds that are extracted from plants or synthesized in the laboratory. The first antitumour metal complex, cis-diamminodichloroplatinum(II), cisplatin, was approved for use in 1979 and is now the leading anticancer drug in the USA [1]. Research developments aimed at reducing side effects, such as nephrotoxicity in the case of cisplatin, has led to a second generation of platinum antitumour compounds [2], such as carboplatin, cis-diammin(cyclobutane-1,1-dicarboxylato)platinum(II). The National Cancer Institute (NCI) has tested 1583 platinum complexes [3].

The target in the cell for active Pt complexes is DNA. Cisplatin and its analogues interact with it by cross-linking suitably oriented bases in DNA to the metal. This blocking mechanism stops the reproduction of cancerous cells and thus inhibits their activity.

Because of these encouraging results, other metal complexes have also been investigated as potential anticancer agents. Since the first report on the antitumour activity of diorganotins appeared in 1980 [4], an increasing number of tin compounds have been studied. Over 2000 tin compounds have been tested by the NCI [3] making tin the metal with the highest number of compounds screened for antitumour activity.

When diorganotin(IV) compounds, R_2SnX_2, X = anion, are treated with appropriate nitrogen chelating ligands, octahedral complexes are obtained that resemble effective Pt complexes [5]. A structural correlation with biological activity for diorganotin complexes has

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shown that inactive species are associated with more stable complexes having Sn–N bond lengths of < 2.39 Å. This observation suggests that higher activity is due to dissociation of the nitrogen ligand as part of the mechanism for inhibition [6]. To a lesser extent tri-organotins are also active and it has recently been shown that a tetraorganotin(IV) with an easily cleaved Sn–C bond is active against four tumour cell lines [7]. Apparently, R_2Sn^{2+} or R_3Sn^+ are ultimately the active species in the biological activity. This suggests a mechanism of action different from that accepted for Pt complexes, where the Pt–N bonds are believed to be retained after interaction with DNA.

We are studying diorganotin(IV) complexes of the ligand 2,2'-bipyrimidine (henceforth called bipym), which is well suited for cis coordination in octahedral complexes, and recently presented evidence shows that in the complexes R_2SnCl_2bipym, R = n-butyl [8] and phenyl [9], the metal acquires a lower coordination number in solution because of the lability of the Sn–N bond. Further indication of the lability of Sn–N bonds involving non-chelating N-ligands has been obtained for pyrazole [10] and pyrazine [11] complexes.

We report here on the synthesis, IR, Mössbauer and NMR spectroscopy and X-ray diffraction studies of bipym–tin complexes which show differing stoichiometries in the solid state and are potentially more active species than those recently reported [8,9].

2. Experimental

2.1. Materials and methods

Me_2SnCl_2 was a gift from Schering (Bergkamen, Germany) and was recrystallized from benzene. Et_2SnCl_2 was purchased from Fluka (Zürich, Switzerland) and used as received. 2,2'-Bipyrimidine was purchased from Ventron-Alfa Inorganics (Beverly, USA) and recrystallized from ethanol. Deuteriated chloroform and methanol were Merck (Darmstadt, Germany) Uvasol reagents with deuterium contents of > 99.9% and > 99%, respectively.

The Mössbauer spectra were obtained as described previously [12] at liquid-nitrogen temperature with a $Ca^{119}SnO_3$ source. Solids or quickly frozen solutions were used.

The IR spectra were recorded on a Perkin-Elmer 983 IR spectrometer in the 4000–200 cm^{-1} region in Nujol or with hexachlorobutadiene mulls between CsI discs or in KBr discs.

The ^1H and ^{13}C NMR spectra were recorded with a Bruker AC200 (B_0 = 4.7 T) or an AM400 (B_0 = 9.4 T) spectrometer. The deuterium signal of the solvent was used for field-frequency lock; chemical shifts are given relative to TMS (δ = 0.00 ppm). Broadband proton decoupling was employed for the ^{13}C spectra; the temperature was 300 K.

Table 1
Summary of crystal data for Et_2SnCl_2bipym · bipym and $(Et_2SnCl_2)_2$bipym

Parameter	Et_2SnCl_2bipym · bipym	$(Et_2SnCl_2)_2$bipym
Formula	$C_{20}H_{22}Cl_2N_8Sn$	$C_{16}H_{26}Cl_4N_4Sn_2$
FW	508.04	653.60
a (Å)	7.728(2)	9.463(3)
b (Å)	11.154(3)	10.823(3)
c (Å)	14.716(3)	11.485(3)
α (°)	106.14(2)	90
β (°)	105.53(2)	100.51(2)
γ (°)	94.87(2)	90
V (Å³)	1156.5(5)	1156.6(6)
Space group	$P-1$	$P2_1/n$
Z	2	2
Crystal size (mm)	0.15 × 0.30 × 0.40	0.20 × 0.20 × 0.25
Density calc. (g cm⁻³)	1.459	1.878
F(000)	508	636
μ (cm⁻¹)	113.29	26.372
Radiation	Cu Kα	Mo Kα
Diffractometer	Syntex P2₁	Nicolet R3
Scan mode	$2\theta - \theta$	$2\theta - \theta$
Scan range (°)	1.6	1.8
Background	1/4 scan time at the end of scan	–
2θ limits (°)	3–140	3–56
Data collected	4763	3235
Data refined, $F_0^2 > 3\sigma(F_0^2)$	3783	2114
Final variables	280	118
Final R, R_w	0.058, 0.077	0.054, 0.095

Table 2
Analytical data and relevant IR frequencies

No.	Compound	M.p. (°C)	C (%) found (calc.)	H (%) found (calc.)	N (%) found (calc.)	Cl (%) found (calc.)	ν(Sn–C)$_{as}$ (cm^{-1})	ν(Sn–C)$_s$ (cm^{-1})	ν(Sn–Cl)$_{as}$ (cm^{-1})
I	(Me$_2$SnCl$_2$)$_2$bipym	190–195	24.03 (24.12)	2.91 (3.04)	9.16 (9.38)		577m		268s,bd
II	(Et$_2$SnCl$_2$)$_2$bipym	150–153	31.18 (29.40)	3.79 (4.00)	9.90 (8.57)		533m	482m	245s,bd
III	Et$_2$SnCl$_2$bipym	145–150	34.70 (35.53)	4.00 (3.97)	12.65 (13.81)	17.94 (17.47)	533m	482m	245s,bd
IV	Et$_2$SnCl$_2$bipym · bipym	155–157	42.70 (42.59)	3.76 (3.93)	19.04 (19.87)		533m	482m	245s,bd

A summary of crystal data and details of the data collection are given in Table 1. Monitoring of three standard reflections ([0,0,2], [0,0,– 2] and [0,0,4]) taken every 100 reflections indicated no decay for the binuclear complex (Et$_2$SnCl$_2$)$_2$bipym and no absorption by the crystal was found. There was no decay for the mononuclear Et$_2$SnCl$_2$bipym · bipym compound (four check reflections ([0,0,1], [0,0,– 1], [1,0,– 1] and [0,2,1]) but absorption was observed by performing a Ψ-scan of some suitable reflections with the χ angle close to 90°. These reflections ([–3,1,3], [–3,– 1,2] and [–4,– 1,2]) showed a minimum transmission of 25%, and so appropriate correction was applied. Both sets of data were corrected for Lorentz and polarization effects. The structures were solved using the Patterson function to locate the Sn and Cl atoms. From the Fourier analysis the positions of the remaining non-H atoms were obtained. Refinement by least-square procedures was then carried out. The minimized function $\Sigma\omega(|F_o| - |F_c|)^2$ had the weighting scheme $\omega = 1/(a + F_o + cF_o^2)$ where a and c are of the order of $2F_o$(min) and $2/F_o$(max) [13]. Hydrogen was introduced in fixed positions, C–H distance = 0.96 Å; C–C–H angle = 109.4° for ethyl groups and on the bisector of the C–C–C or N–C–C moieties for aromatic groups. All the non-H atoms were refined anisotropically. The calculations were performed on a VAX 3300 computer using the CAOS program [14].

Atomic scattering factors and anomalous dispersion terms were taken from the International Tables for X-Ray Crystallography.

2.2. Synthesis of the compounds

The adducts I–IV in Table 2, were obtained as white solids by mixing hot cyclohexane solutions of the reagents in appropriate stoichiometric amounts, i.e. with an organotin to ligand ratio of 1 : 1 for I and III, 3 : 2 for II and 1 : 2 for IV. The adducts were recrystallized from dichloromethane–cyclohexane (1 : 1). Analytical data are reported in Table 2.

The ligand bipym reacts with Me$_2$SnCl$_2$ to give a unique complex having a 2 : 1 organometal to ligand ratio, I (Table 2). Its composition suggests the forma-

Table 3
Mössbauer data

No.	Compound	IS [a] (mm s^{-1})	QS (mm s^{-1})	$\Gamma_{\pm}$ (mm s^{-1})
I	(Me$_2$SnCl$_2$)$_2$bipym	1.44	4.06	0.88
II	(Et$_2$SnCl$_2$)$_2$bipym	1.61	4.16	0.93
III	Et$_2$SnCl$_2$bipym	1.59	4.05	0.85
IV	Et$_2$SnCl$_2$bipym · bipym	1.64	4.17	0.88
		1.66 [b]	4.18 [b]	0.78 [b]
V	(Me$_2$SnCl$_2$)$_2$Pyz	1.41 [c]	3.36 [c]	0.80 [c]
VI	Me$_2$SnBr$_2$Pyz	1.49 [c]	4.10 [c]	
		1.49 [b]	3.91 [b]	0.94 [b]
		1.28 [d]	4.25 [d]	0.82 [c]
VII	Me$_2$SnCl$_2$Azp	1.48 [e]	3.80 [e]	0.91
VIII	Me$_2$SnBr$_2$Azp	1.59 [e]	4.06 [e]	0.92
		1.58 [b]	3.90 [b]	0.82 [b]

[a] With respect to a room-temperature spectrum of CaSnO$_3$.
[b] Dichloromethane frozen solution.
[c] Ref. [15].
[d] Ethanolic frozen solution.
[e] Ref. [16].

tion of a monomeric species with the ligand bridging. The reaction of bipym with Et_2SnCl_2, in contrast, gives rise to complexes with varying stoichiometric composition, II–IV.

3. Results and discussion

3.1. IR and Mössbauer spectral results

The relevant IR frequencies of the newly prepared compounds are shown in Table 2 and their Mössbauer parameters (isomer shift, IS, quadrupole splitting, QS, and full width at half-height, $\Gamma_{\pm}$) are listed in Table 3 together with those for previously reported diorganotin–nitrogen base complexes [15,16].

The IS values for the solids are typical of quadrivalent organotin derivatives [17]. The IS value is lower for Me_2SnCl_2 adducts than Et_2SnCl_2 derivatives, in keeping with the larger hyperconjugation of the methyl group bound to the tin atom. The same IS values are found for dichloromethane solutions.

The QS values are unambiguously indicative of a octahedral configuration of the tin atom with trans alkyl groups [18]. Using the Parish relationship between the QS and the C–Sn–C bond angle, θ [18], the values of θ

were calculated for solid and solution phases (Table 4) and good agreement was found for the solids between the calculated values and those determined by diffraction studies [15,16]. In dichloromethane the QS value remains constant for Et_2SnCl_2bipym · bipym but decreases slightly for Me_2SnBr_2Azp and Me_2SnBr_2Pyz adducts, indicating a small conformational variation with narrowing of the C–Sn–C bond angle. In frozen ethanol solution the QS of Me_2SnBr_2Pyz unambiguously indicates an octahedral arrangement at the tin atom, with possible coordination of a solvent molecule.

As far as the IR spectra are concerned, it can be seen that the strong bands at 1558 and 1547 cm^{-1} assigned to C=N and C=C stretchings [19] appear as a single broad band at 1570 cm^{-1} for the adducts $(R_2SnCl_2)_2$bipym (R = Me, Et), but are split into three bands (1588, 1569, 1553 cm^{-1}) in the case of Et_2SnCl_2bipym and Et_2SnCl_2bipym · bipym. In the first case the degeneracy of the absorptions points to the equivalence of the ligand nitrogens relative to the diorganotin moiety, in the second case the splitting suggests the presence of complexes in which only two of the four nitrogen atoms are coordinated [20], in agreement with the crystal structure found for Et_2SnCl_2bipym · bipym (see below).

The $(Sn–C)_{as,s}$ stretchings coincide for the Et_2SnCl_2 complexes II–IV (Table 2), the values being unaffected

Table 4
Values of the C–Sn–C θ angle (°) measured by diffraction or calculated from parameters obtained by different techniques (as indicated at the top of the columns)

Compound	^{1}H NMR [a]	^{13}C NMR [b]	^{119}Sn Mössbauer		Diffraction
			Solids	Frozen solutions	
Me_2SnBr_2	116	115			
Me_2SnBr_2Pyz	117		173 [c]	159 [d]	180 [c]
				180 [e]	
$(Me_2SnCl_2)_2Pyz$	120	120	138 [c]		136.5 [c]
Me_2SnCl_2	117	119			123.5 [f]
	151 [g]	145 [g]			
Me_2SnCl_2Azp	128	129	153 [h]		
Me_2SnBr_2Azp	124		169 [h]	159	162 [h]
$(Me_2SnCl_2)_2$bipym	153	145	169		
	169 [i]	154 [j]			
$(Et_2SnCl_2)_2$bipym	117	134	180		174.6
	107 [i]	130 [j]			
Et_2SnCl_2bipym	135	149	180		
	143 [i]	161 [j]			
Et_2SnCl_2bipym · bipym	130	146	180		171.7
	135 [i]	155 [j]			
Et_2SnCl_2	110	115			134.0 [f]

[a] From Eq. (2) or (2′).
[b] From Eq. (1).
[c] Ref. [15].
[d] Dichloromethane solution.
[e] Ethanol solution.
[f] Ref. [27].
[g] Methanol solution.
[h] Ref. [16].
[i] From Eq. (3).
[j] From Eq. (4).

Table 5
Atomic coordinates for $(Et_2SnCl_2)_2$bipym

Atom	x	y	z
Sn(1)	0.4164(1)	0.3103(1)	0.6991(1)
Cl(1)	0.5826(3)	0.1530(3)	0.8098(3)
Cl(2)	0.1750(4)	0.2381(4)	0.7538(3)
C(1A)	0.5726(9)	0.4726(8)	0.5096(7)
N(2A)	0.6082(9)	0.3902(8)	0.5959(7)
C(3A)	0.737(1)	0.343(1)	0.609(1)
C(4A)	0.8363(9)	0.375(1)	0.5359(9)
C(5A)	0.792(1)	0.4626(9)	0.451(1)
N(6A)	0.6613(8)	0.5124(8)	0.4371(7)
C(1)	0.356(1)	0.188(1)	0.551(1)
C(2)	0.451(2)	0.168(2)	0.470(2)
C(3)	0.469(1)	0.4460(9)	0.8353(8)
C(4)	0.601(1)	0.5260(9)	0.8345(8)

by the differing ligand modes; only the $(Sn–C)_{as}$ at 577 cm^{-1} and $(Sn–Cl)_{as}$ at 268 cm^{-1} have been reliably assigned in the case of the $(Me_2SnCl_2)_2$bipym adducts.

3.2. Diffraction study

Atomic coordinates for compounds II and IV are given in Tables 5 and 6. Figs. 1 and 2 show views of both complexes. A stereo view of the packing for the

Table 6
Atomic coordinates for Et_2SnCl_2bipym·bipym

Atom	x	y	z
Sn(1)	0.1430(1)	0.14564(3)	0.33745(3)
Cl(1)	−0.0787(3)	0.0823(2)	0.1659(1)
Cl(2)	0.2422(3)	−0.0533(2)	0.3680(1)
N(2A)	0.1137(7)	0.3686(5)	0.3648(4)
N(6A)	0.219(1)	0.5813(5)	0.4715(4)
N(2B)	0.3240(8)	0.2848(5)	0.5025(4)
N(6B)	0.388(1)	0.4897(6)	0.6217(4)
C(1)	−0.069(1)	0.1306(8)	0.4034(6)
C(2)	−0.199(1)	0.007(1)	0.3610(8)
C(3)	0.377(1)	0.1824(8)	0.2904(7)
C(4)	0.384(1)	0.0803(9)	0.1990(7)
C(1A)	0.211(1)	0.4576(6)	0.4518(5)
C(3A)	0.018(1)	0.4113(7)	0.2942(5)
C(4A)	0.017(1)	0.5386(7)	0.3080(6)
C(5A)	0.124(1)	0.6202(7)	0.3977(6)
C(1B)	0.313(1)	0.4088(6)	0.5306(5)
C(3B)	0.423(1)	0.2401(7)	0.5727(5)
C(4B)	0.502(1)	0.3169(8)	0.6684(6)
C(5B)	0.478(1)	0.4406(8)	0.6900(6)
N(12A)	0.111(1)	0.3818(6)	0.8990(5)
N(16A)	0.223(1)	0.4214(6)	1.0727(5)
N(12B)	0.298(1)	0.6068(7)	0.9174(5)
N(16B)	0.417(1)	0.6450(7)	1.0911(5)
C(11A)	0.208(1)	0.4520(7)	0.9899(5)
C(13A)	0.019(1)	0.2708(8)	0.8905(6)
C(14A)	0.020(1)	0.2305(8)	0.9720(7)
C(15A)	0.126(1)	0.3098(8)	1.0608(7)
C(11B)	0.314(1)	0.5761(7)	1.0000(5)
C(13B)	0.395(1)	0.7186(9)	0.9295(8)
C(14B)	0.503(1)	0.7960(9)	1.0195(8)
C(15B)	0.511(2)	0.7558(9)	1.0978(8)
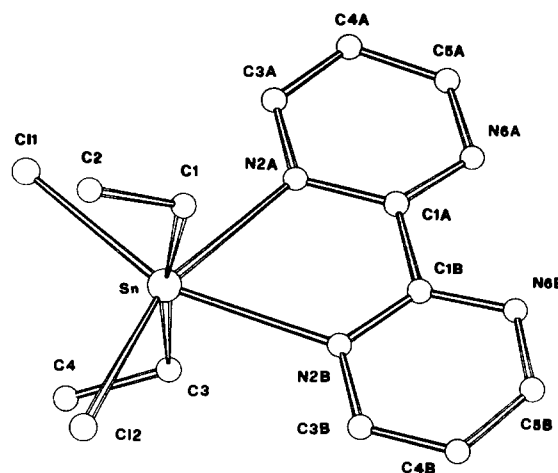
Fig. 1. A view of Et_2SnCl_2bipym·bipym with H atoms and the free ligand bipym omitted.

complex IV is given in Fig. 3, and Table 7 shows selected bond distances and angles. In the mononuclear compound IV the tin atom is surrounded by two ethyl groups, two Cl atoms and two N atoms from a bipym ligand, in an octahedral configuration. There is no bonding interaction with the second ligand, and so this crystalline compound is formally Et_2SnCl_2bipym·bipym. The structure of the complex is similar to those of two complexes recently reported, namely, Ph_2SnCl_2bipym [9] and Bu_2SnCl_2bipym [8], with the ethyl groups replaced by phenyl or butyl groups, respectively.

Although the tin environment is the same in the binuclear complex II, this compound differs from the others in that the ligand is coordinated, through the second set of N atoms to another Et_2SnCl_2 unit. The species has a crystallographic centre of symmetry at the midpoint of the C(1A)–C(1B) bond (Fig. 2). Table 8 shows structural features of the two complexes of this work along with those for the two previously reported. All the compounds in Table 8 have the equal Sn–C bond lengths, a common feature in diorganotin derivatives. The Sn–Cl bonds are similar for complexes with alkyl substituents but significantly shorter for the phenyl
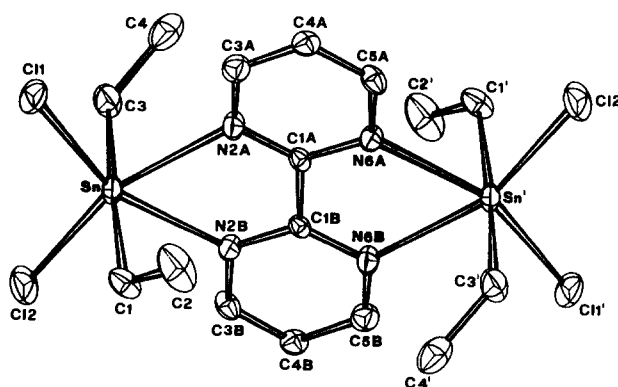

Fig. 2. A view of $(Et_2SnCl_2)_2$bipym with H atoms omitted.

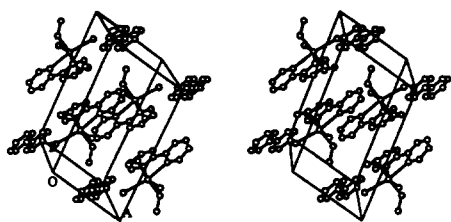Fig. 3. Stereo view of the packing for the complex Et₂SnCl₂bipym·bipym. The molecules are located in the area −0.3, 1.3 (x); −0.3, 1.3 (y); −0.3, 1.3 (z).

complex, which also shows shorter Sn-N bond distances than the alkyltin complexes. This effect may be ascribed to the greater electron withdrawal by the phenyl group, which acts in such a way as to increase the s-character in the plane perpendicular to the C–Sn–C axis. Another notable feature is the N–N bite angle, which is 67.9° for the phenyl derivative, whereas in the others it is ca. 66°. Again, the phenyl compound shows the smallest C–Sn–C angle, 169.3(2)°, among the complexes in Table 8.

The Sn-N bonds in II, 2.496(8) and 2.500(9) Å, are significantly longer than those in complex IV (2.446(6) and 2.446(8) Å) and longer than those in the butyl complex (2.46(1) and 2.472(9) Å). According to Crowe et al. [6], diorganotins with Sn-N bonds longer than 2.39 Å are associated with antitumour activity. On this basis, II and IV should be active and the dinuclear compound the most promising of those in Table 8.

Since compound IV also contains free bipym of solvation, it is of interest to note the changes in the ligand structure on coordination. In addition to a non-significant lengthening of the N(2A)–C and N(2B)–C bonds on coordination there is an interesting in-plane folding of the aromatic rings in the coordinated bipym.

Table 7
Bond distances and angles in the coordination sphere of dichlorodiethyltin-2,2'-bipyrimidine complexes

	Et₂SnCl₂ bipym·bipym	(Et₂SnCl₂)₂ bipym
Distances (Å)		
Sn-Cl(1)	2.508(2)	2.502(4)
Sn-Cl(2)	2.525(2)	2.495(4)
Sn-C(1)	2.134(8)	2.15(1)
Sn-C(3)	2.148(9)	2.14(1)
Sn-N(2A)	2.446(6)	2.496(8)
Sn-N(2B)	2.446(8)	2.500(9)
Angles (°)		
Cl(2)-Sn-Cl(1)	107.47(8)	108.1(1)
C(1)-Sn-C(3)	171.7(5)	174.6(4)
N(2A)-Sn-N(2B)	66.4(2)	66.0(3)
N(2A)-Sn-Cl(1)	91.7(2)	91.9(2)
N(2A)-Sn-Cl(2)	160.8(2)	159.9(2)
N(2A)-Sn-C(1)	87.0(3)	87.1(3)
N(2A)-Sn-C(3)	88.3(3)	91.0(3)
N(2B)-Sn-Cl(1)	158.0(1)	157.8(2)
N(2B)-Sn-Cl(2)	94.4(1)	94.0(2)
N(2B)-Sn-C(1)	85.2(3)	88.4(4)
N(2B)-Sn-C(3)	86.7(4)	86.2(3)
Cl(2)-Sn-C(1)	91.4(2)	90.2(3)
Cl(2)-Sn-C(3)	90.8(2)	89.9(3)
Cl(1)-Sn-C(1)	92.5(3)	92.0(3)
Cl(1)-Sn-C(3)	94.4(3)	93.1(3)

This rotation about the C(1)–Sn–C(3) axis brings the coordinated nitrogen atoms, N(2A) and N(2B), closer to one another than those not coordinated, N(6A) and N(6B) (Table 9). This effect was also found in Ph₂SnCl₂bipym [9] and Bu₂SnCl₂bipym [8] (for instance, N(2A) ··· N(2B) are 2.687(6) Å and 2.70(1) Å, respectively). Also included in Table 9 is the torsion angle N(2A)–C(1A)–C(1B)–N(2B), which provides a

Table 8
Structural parameters for 2,2'-bipyrimidine–dichlorodi-R-tin complexes

	R = Ph	R = n–Bu	R = Et (IV [a])	R = Et (II [a,b])
Distances (Å)				
Sn-Cl	2.451(2)	2.508(2)	2.508(2)	2.495(4)
	2.466(2)	2.525(2)	2.525(2)	2.502(4)
Sn-C	2.139(7)	2.14(1)	2.134(8)	2.14(1)
	2.141(7)	2.14(1)	2.148(9)	2.15(1)
Sn-N	2.398(4)	2.46(1)	2.446(6)	2.496(8)
	2.413(4)	2.472(9)	2.446(8)	2.500(9)
Angles (°)				
C-Sn-C	169.3(2)	175.1(6)	171.7(2)	174.6(4)
Cl-Sn-Cl	103.81(5)	106.0(1)	107.47(8)	108.1(1)
N-Sn-N	67.9(1)	66.4(3)	66.4(2)	66.0(3)
Ref.	[9]	[8]	This work	This work

[a] See Table 2.
[b] II has two diethyldichlorotin units bound to bipym; since the compound is centrosymmetric, the data shown here refer to both units.

Table 9
Deformations (twist and in-plane folding) in the ligand bipym

	[N(2A)–C(1A)–C(2B)–N(2B)] [a]	N(2A) $\cdots$ N(2b) [b]	N(6A) $\cdots$ N(6B) [b]
Ligand	1(1)	2.69(1)	2.70(1)
Mononuclear complex (IV)	11(1)	2.677(8)	2.751(9)
Dinuclear complex (II)	0	2.72(1)	2.72(1)

[a] Torsion angle (°).

[b] Non-bonding distances (Å).

measure of the twist of the aromatic moieties; the value for the mononuclear complex, 11(1)°, is much larger than that for the free ligand, 1(1)°. Such a twisting was found also in Ph_2SnCl_2bipym and Bu_2SnCl_2bipym, although it was not as large (the torsion angles are 8.2(7) and 4(1)°, respectively). Hence there is a partial loss of the ligand planarity on coordination. However, the planarity is restored on coordination of a second Et_2SnCl_2 unit, since the binuclear complex has a 0° torsion angle. The in-plane folding of the aromatic rings observed in the mononuclear complex is absent in the case of the binuclear species, the N(2A)–N(2B) and

N(6A)–N(6B) distances being equivalent by crystallographic symmetry.

3.3. NMR spectral results

The ^{13}C and ^{1}H NMR data for the complexes discussed here, and for relevant compounds and for related compounds described elsewhere [8,15,16], are listed in Tables 10 and 11, respectively. The coupling constants $^{1}J(^{119}Sn, ^{13}C)$ and $^{2}J(^{119}Sn, ^{1}H)$ were used to determine the C–Sn–C bond angles, θ, by use of either the Lockhart and co-workers [21,22] or the Howard equa-

Table 10
^{13}C NMR data for chloroform-d_1 solutions (B_0 = 4.7 or 9.4 T; T = 298 K; TMS δ = 0.00 ppm; $^{n}J(Sn,^{13}C)$ [a] in Hz in parentheses)

Compound	δ (ppm)						
	Me or Et		Ligand				
	C_α	C_β	C_2	C_3	C_4	C_5	C_6
Me_2SnBr_2	7.26 (^{1}J = 421.1)						
Me_2SnBr_2Pyz	7.46 [b]		145.16	145.16		145.16	145.16
Pyz [c]			145.6	145.6		145.6	145.6
$(Me_2SnCl_2)_2$Pyz	6.56 (^{1}J = 485.5)		145.00	145.00		145.00	145.00
Me_2SnCl_2	6.33 (^{1}J = 477.6)						
Me_2SnCl_2Azp	11.44 (^{1}J = 600.2)		160.69	116.99	139.66	126.96	149.05
Azp			162.57	115.33	138.38	126.01	149.55
Me_2SnBr_2Azp	9.05 [b]		162.57	115.68	138.55	126.20	149.58
Me_2SnCl_2 [d]	13.83 (^{1}J = 776.7)						
$(Me_2SnCl_2)_2$bipym [d]	13.91 (^{1}J = 782.5)		162.96		159.63	123.90	159.63
Bipym			162.22		157.90	121.37	157.90
$(Et_2SnCl_2)_2$bipym	25.11 (^{1}J = 646.6)	9.74 (^{2}J = 45.0)	158.88		158.26	122.84	158.26
Et_2SnCl_2bipym	30.69 (^{1}J = 820.0)	10.33 (^{2}J = 50.4)			158.34	123.25	158.34
Et_2SnCl_2bipym · bipym	29.76 (^{1}J = 789.9)	10.19 (^{2}J = 39.9)	160.47		158.10	122.15	158.10
Et_2SnCl_2	18.22 (^{1}J = 433.3)	9.08 (^{2}J = 39.9)					

[a] The value for the 119 isotope is reported when ^{119}Sn and ^{117}Sn satellites are resolved.

[b] Satellites undetectable.

[c] In water solution, from Ref. [31].

[d] In methanol-d_4.

Table 11
^{1}H NMR data for chloroform-d_1 solutions (B_0 = 4.7 or 9.4 T; T = 298 K; TMS δ = 0.00 ppm; $^nJ(Sn,^1H)$ [a] in Hz in parentheses)

Compound	δ (ppm)						
	Me or Et		Ligand				
	H_α	H_β	H_2	H_3	H_4	H_5	H_6
Me$_2$SnBr$_2$	1.23 (^2J = 66.1)						
Me$_2$SnBr$_2$Pyz	1.37 (^2J = 66.3)		8.60	8.60		8.60	8.60
Pyz [b]			8.63	8.63		8.63	8.63
(Me$_2$SnCl$_2$)$_2$Pyz	1.20 (^2J = 69.7)		8.60	8.60		8.60	8.60
Me$_2$SnCl$_2$	1.20 (^2J = 68.7)						
Me$_2$SnCl$_2$Azp	1.20 (^2J = 77.7)		c	c		7.51	8.86
Azp			c	c		7.46	8.78
Me$_2$SnBr$_2$Azp	1.37 (^2J = 73.8)		c	c		7.52	8.87
Me$_2$SnCl$_2$ [d]	1.21 (^2J = 94.0)						
	1.18 (^2J = 94.6)				9.11	7.74	9.11
Bipym				8.99	7.41	8.99	
(Et$_2$SnCl$_2$)$_2$bipym	1.69 (^2J = 67.1)	1.31 (^3J = 155.3)		9.27	7.66	9.27	
(Et$_2$SnCl$_2$)bipym	1.60 (^2J = 83.0)	1.15 (^3J = 172.9)		9.31	7.75	9.31	
Et$_2$SnCl$_2$bipym · bipym	1.64 (^2J = 79.4)	1.22 (^3J = 169.2)		9.14	7.55	9.14	
Et$_2$SnCl$_2$	1.76 (^2J = 49.4)	1.43 (^3J = 135.2)					

[a] The value for the 119 isotope is reported when ^{119}Sn and ^{117}Sn satellites are resolved.
[b] In water solution, from Ref. [32].
[c] Overlapping multiplets, centred at 8.0 ppm.
[d] In methanol-d_4.

tion [23]. The calculated θ values are listed in Table 4 together with those obtained from Mössbauer ΔE parameters or determined by X-ray diffractometry.

The ^{1}H and ^{13}C NMR spectral parameters for Me$_2$SnCl$_2$, Me$_2$SnBr$_2$ and Et$_2$SnCl$_2$ in chloroform solution are consistent with published data [24,25]. The θ values were calculated from the coupling constants by means of the equation [21]

$$| ^1J(^{119}Sn, ^{13}C) | = 11.4\theta - 875 \quad (1)$$

and the equations [22]

$$\theta = 0.0105 | ^2J(^{119}Sn, ^1H) |^2$$
$$- 0.799 | ^2J(^{119}Sn, ^1H) | + 122.4 \quad (2)$$

for dimethyltin(IV) dihalides and

$$\theta = 0.0161 | ^2J(^{119}Sn, ^1H) |^2$$
$$- 1.32 | ^2J(^{119}Sn, ^1H) | + 133.4 \quad (2')$$

for the remaining compounds (see Table 4).

The values obtained for each compound from the above equations are in excellent agreement with one

another and are slightly lower than the crystallographic values reported for Me$_2$SnCl$_2$ (θ = 123.5° [26]) and Et$_2$SnCl$_2$ (θ = 134.0° [27]). Comparable discrepancies have often been reported [21,23,28,29] and are not unexpected in view of the empirical nature of the equations. However, a role could also be attributed to solvent effects, leading to an averaged five-coordinate environment of tin as a result of fast (on the NMR time-scale) breaking and formation of the halogen bridges present in the highly distorted octahedral tin coordination sphere in the solid state [27]. In methanol solution, tin is expected to be six-coordinate with two methyl groups, two Cl atoms and two solvent molecules in an all-trans configuration. The estimated θ values do, indeed, suggest a trans arrangement of the alkyl groups if the lability of the solvent coordination is taken into account.

Turning to the Azp complexes, it can be seen that the Mössbauer QS parameter, determined either for the solid state or for a frozen solution at 77.3°K (Table 3), yields θ values in good agreement with those obtained by diffraction and in keeping with a distorted trans

octahedral geometry (Table 4). The NMR data in solution at room temperature, in contrast, suggest a different, lower, coordination around tin. The coupling constants $^2J(^{119}Sn, {}^1H)$ and $^1J(^{119}Sn, {}^{13}C)$, on the other hand, are larger for the adducts than for the free acceptors, in keeping with a tin coordination number larger than four. Moreover, the ligand protons, as well as the methyl protons in Me_2SnBr_2 Azp (Table 11) are slightly deshielded on complexation. Much larger effects are found in the case of the ^{13}C chemical shifts (Table 10), i.e. a deshielding of several ppm for the methyl carbons and a slight upfield shift of the C_2 carbons. These data suggest that in solution the adducts are still present, but with a coordination number of five around tin and in a trigonal bipyramidal geometry with equatorial alkyls. This average structure could arise from fast dissociation equilibria of the adducts, as has been observed for similar complexes [9,10], and this mechanism is supported by the θ values (Table 4) calculated either from Eqs. (1) and (2′), or by means of the equations proposed by Howard et al. [23] for octahedral dialkyltin(IV) complexes:

$$\theta = 2.28\,|\,^2J(^{119}Sn, {}^1H)\,|\,-46.4 \tag{3}$$

and

$$\theta = 0.178\,|\,^1J(^{119}Sn, {}^{13}C)\,|\,+14.74 \tag{4}$$

Very small differences are observed in the case of the pyrazine adducts, in respect both of the chemical shift data and of the coupling constants values, relative to free ligand and free organotins. A small (0.56 ppm) downfield shift for the methyl carbons and a negligible increase in ^1J are observed for the chloride complex. The θ values calculated from the NMR parameters are consistent with the reported five-coordination for tin in a trigonal bipyramidal geometry with equatorial alkyls and a bridging pyrazine molecule [15].

The bromide adduct, on the other hand, is polymeric in the solid state, with bridging bis-monodentate pyrazine between the organotin moieties and all-trans octahedral coordination [15]. The C–Sn–C angle calculated from the Mössbauer QS parameter for the solid is practically coincident with that obtained by diffraction, and the value obtained for the frozen solution is only slightly smaller. On the other hand, the value of θ derived from the ^2J value (117°) for a solution at room temperature indicates breaking of the pyrazine bridges leading to an average five-coordination for tin in a monomeric complex.

An interesting comparison can be made between the two bipym complexes $(Me_2SnCl_2)_2$bipym and $(Et_2 SnCl_2)_2$bipym. Mössbauer point charge calculations assign a trans-octahedral geometry to both adducts in the solid state (Table 4), and this is supported in the case of the ethyl derivative by the X-ray structural data ($\theta =$ 174.6°). In solution, however, a strong solvent influence

is observed. The octahedral geometry found for $(Et_2SnCl_2)_2$bipym by diffraction and calculated from ^{119}Sn Mössbauer QS parameter in the solid, with a trans arrangement of the two alkyl groups, appears to be destroyed in the non-coordinating solvent. The NMR coupling constants ^1J and ^2J yield θ values that suggest a trigonal distorted bipyramid for the coordination polyhedron of tin, with the two ethyls in the equatorial plane. Moreover, if θ is determined by use of the Howard equations [23], which were derived for octahedral complexes, the discrepancy is so large as to suggest that the equations are not in fact applicable because of non-octahedral geometry around tin.

Breaking one of the tin–nitrogen bonds probably takes place for the dimethyl derivative also, but the free coordination position would be occupied by a solvent molecule, restoring the octahedral geometry. Indeed, the C–Sn–C angle derived from the ^2J value by means of Eq. (3) [23] is the same as that calculated for the solid from the Mössbauer spectral parameter QS. The deshielding of the ligand protons relative to those in the free donor, and the increase in ^2J with respect to that for the free acceptor, for the 1 : 1 Et_2SnCl_2bipym adduct indicate that binding of bipym is retained in solution. However, the θ value calculated from ^1J and ^2J (Table 4), which is clearly lower than 180°, i.e. the angle derived from Mössbauer measurements on the solid, suggests again the existence in solution of an equilibrium, fast on the NMR time-scale, between monodentate and chelating ligands. The average coordination number of tin would then be intermediate between six and five. A similar description applies to the 1 : 2 adduct, which in the solid state has been shown by diffraction to consist of the 1 : 1 complex and one free ligand molecule. In solution, an equilibrium can be suggested between free and either monodentate or chelating bipym, leading to the same average coordination number and θ angle of the 1 : 1 complex. The chemical shift values, of both carbons and protons, are slightly closer to those of the free organotin and bipym than is observed for the 1 : 1 adduct, in agreement with an equilibrium suggested as

$$(Et_2SnCl_2bipym) \cdot bipym \rightleftharpoons Et_2SnCl_2 + 2bipym \tag{5}$$
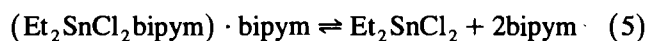
with the bound ligand acting as mono- or bi-dentate. Such a labile coordination in solution has been observed not only for pyrazole [10] but also for the 2-mercaptopyrimidine ligand in organotin(IV) complexes [30].

4. Conclusions

Diorganotins R_2SnCl_2 (R = Me, Et, ^nBu and Ph) react with bipym to yield crystalline octahedral monomeric complexes of various stoicheiometries, as reported here and in previous papers [8,9]. However, the

nitrogen ligand has been found to be labile in solutions in the non-coordinating solvent chloroform. Average coordination numbers of less than 6 and C–Sn–C angles markedly less than 180° have been derived from solution NMR measurements at room temperature. Such an easy breaking of the Sn–N bond is in accord with the relatively long bond distances found by diffraction methods for $(Et_2SnCl_2)_2$bipym and Et_2SnCl_2bipym · bipym and for R_2SnCl_2bipym adducts, R = n-butyl [8] and phenyl [9]. Similar behaviour in solution has been observed also for the 2,2'-azopyridine and pyrazine complexes, as shown in Table 4, and also reported for organotin(IV) complexes of 2-mercaptopyrimidine [30] and pyrazine [11]

The Sn–N bond length in such complexes is always > 2.39 Å. Since the antitumour activity of organotin(IV) complexes with nitrogen donors is thought to be associated with Sn–N bonds longer than 2.39 Å and labile [6], the complexes described here could be effective against cancer cells, and seem to be suitable candidates for biological testing.

Acknowledgements

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