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Preparation and Crystal Structure of Tetraphenylarsonium Bis(2-mercaptoethanolato)oxotechnetate

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Received August 7, 1980

Radiopharmaceuticals incorporating ^{99m}Tc are widely used in diagnostic nuclear medicine[2] because of the favorable physical properties of the radionuclide (γ = 140 keV; $t_{1/2}$ = 6 h). The chemical identity of these radiopharmaceuticals is difficult to ascertain because of the very low concentrations (typically 10^{-8} M) in which they are produced. We have been systematically preparing and characterizing complexes of the long-lived isotope ^{99}Tc (β^- = 0.3 MeV; $t_{1/2}$ = 2.12 × 10^5 years) on a macroscopic scale to determine the reactivity and ligand preferences of this element. This is necessary to gain insight into the chemical composition of present radiopharmaceuticals and for the rational design of future ones.

Recent work[3-7] has shown that the reduction of pertechnetate (TcO_4^-) in the presence of a 1,2-dithiol leads to the formation of square-pyramidal complexes of oxotechnetium(V). Donor sets of this type are found in radiopharmaceuticals containing 2,3-dimercaptopropanesulfonate, 2,3-dimercaptosuccinic acid, and dihydrothioctic acid. We felt it would be interesting to examine the effect of changing one of the potentially ligating atoms from sulfur to oxygen and chose β-mercaptoethanol as the simplest model ligand. Reduction of pertechnetate by sodium dithionite in the presence of a 2:1 molar ratio of this ligand yields a crystalline product, identifiable by chemical, spectroscopic, and X-ray diffraction methods as $TcO(SCH_2CH_2O)_2^-$ (**1**), a pseudo-square-pyramidal complex of Tc(V).

Experimental Section

Aqueous $NH_4{}^{99}TcO_4$ was obtained from New England Nuclear. The concentration was determined by a literature method.[8] Sodium dithionite (Fisher) and β-mercaptoethanol (Eastman) were used without further purification. Water was passed through a Barnstead D8904 cartridge for removal of organics and a Corning 3508-B demineralizer cartridge and then distilled with use of a Corning Mega-Pure still. All other solvents were used as received.

Elemental analyses were performed by Spang Microanalytical Laboratory, Eagle Harbor, MI. Solution optical spectra were recorded on a Cary 17 spectrophotometer. Infrared spectra were recorded on a Perkin-Elmer 180 grating spectrophotometer as KBr pellets.

The X-ray structure determination was performed by the crystallographic staff of Molecular Structure Corp., College Station, TX. All calculations were performed on a linked PDP-11/45-11/60 computation system using the Enraf-Nonius structure determination package[9] and private programs of the Molecular Structure Corp.

The crystal used for the collection of the data set had dimensions 0.20 × 0.20 × 0.25 mm. It was mounted with its long axis roughly parallel to the ϕ axis of the goniometer. Details of the data collection are given in Table I.

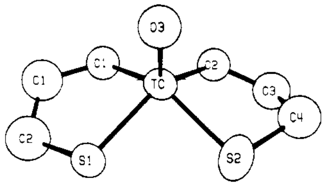

Figure 1. ORTEP drawing of the $[TcO(SCH_2CH_2O)_2]^-$ ion. The numbering scheme is that used for the atoms in Table III.

Table I. Crystal Data for $Ph_4As[TcO(SCH_2CH_2O)_2]$

A. Cell Parameters at 23 °C[a]

crystal system: orthorhombic
space group: *Pbca*
Z = 8
fw 649.58
ρ(calcd) = 1.61 g cm^{-3}
a = 15.039 (2) Å
b = 18.510 (3) Å
c = 19.196 (3) Å
V = 5343.8 Å^3

B. Collection of Intensity Data

diffractometer: Enraf-Nonius CAD4
radiation: Mo Kα (λ = 0.71073 Å)
monochromator: graphite crystal, incident beam
scan type: ω–θ
scan rate: 2–20°/min (in ω)
scan width: 0.6 + 0.350 tan θ
max 2θ: 45.0°
reflctns collected: 3873 total, 3478 unique
stds: 3 every 41 min, no measurable decay
absn coeff: μ = 20.1 cm^{-1}
corrections: Lorentz-polarization

[a] Based on 25 reflections in the range 8° < θ < 18°.

The structure was solved by direct methods using 3478 unique reflections; hydrogen atoms were not included in the calculations. Only the 2555 reflections with $F_o > 3.0\sigma(F_o)$ were used in the full-matrix least-squares refinement, which resulted in final unweighted and weighted agreement factors of R_1 = 0.050 and R_2 = 0.071. The highest peak in the final difference Fourier was 0.47 (4) e Å^{-3}. Final positional and thermal parameters are collected in Table II.

$(C_6H_5)_4As[TcO(SCH_2CH_2O)_2]$. In a typical synthesis, 1 mL of a 0.43 M solution of $NH_4{}^{99}TcO_4$ (0.43 mmol) was diluted with 75 mL of H_2O, and 0.062 mL of neat β-mercaptoethanol (0.88 mmol) was added. A solution of 0.216 g of $Na_2S_2O_4$ (1.24 mmol) in 10 mL of 2 M NaOH was added dropwise to the stirred reaction mixture. After 20 min, several drops of a concentrated solution of Ph_4AsCl in H_2O were added, and a voluminous metallic pink precipitate appeared in the straw yellow mother liquor. The crude product was filtered and washed with H_2O (2 × 2.5 mL) and then dried for 24 h in vacuo. The solid was dissolved in 10 mL of absolute EtOH and filtered. The filtrate was taken to dryness on a rotary evaporator. The residue was dissolved in ca. 5 mL of CH_3CN, and, after addition of an approximately equal volume of Et_2O, the solution was stoppered and stored at −28 °C for 24 h. The crystals were filtered, washed with Et_2O, and air-dried. The overall yield was 0.102 g (0.16 mmol, 53%).

Anal. Calcd for $C_{28}H_{28}AsO_3S_2Tc$: C, 51.69; H, 4.34; As, 11.52; S, 9.86. Found: C, 52.33; H, 4.39; As, 12.41; S, 10.56.

Results and Discussion

Bond lengths and angles for **1** are given in Table III. The distances and angles for the Ph_4As^+ ion are unexceptional and will not be discussed. The structure of the anion is approximately square pyramidal. The basal plane is distorted toward a trapezoid because of the difference between the average Tc–O(ligand) and Tc–S distances (1.950 (4) vs. 2.291 (2) Å, respectively).

The average Tc–S bond length in **1** compares favorably with that of $TcO(SCH_2CH_2S)_2^-$ (**2**) (2.30 (1) Å)[6] and $TcO(SCH_2COS)_2^-$ (**3**) (2.320 (3) Å).[3] The Tc–O(oxo) distance of **1** is also very similar to that of **2** (1.64 (1) Å) and **3** (1.672 (8) Å). However, the metal atom-to-basal plane distance of **1** (0.720 (1) Å) is considerably shorter than that of **2** (0.761 (2)

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0020-1669/81/1320-1617$01.25/0

Table II. Final Positional and Thermal Parameters for $Ph_4As[TcO(SCH_2CH_2O)_2]^a$

atom	*x*	*y*	*z*	*U*(1,1)	*U*(2,2)	*U*(3,3)	*U*(1,2)	*U*(1,3)	*U*(2,3)
Tc	0.560 15 (5)	0.466 46 (4)	0.292 63 (4)	0.0477 (4)	0.0351 (4)	0.0467 (4)	0.0003 (4)	−0.0055 (4)	−0.0113 (4)
As	0.400 86 (5)	0.165 75 (4)	0.457 28 (4)	0.0340 (4)	0.0327 (4)	0.0305 (4)	−0.0003 (4)	−0.0007 (4)	−0.0002 (4)
S_1	0.701 3 (2)	0.427 0 (1)	0.314 3 (1)	0.054 (1)	0.059 (1)	0.058 (1)	0.010 (1)	−0.000 (1)	−0.002 (1)
S_2	0.522 3 (2)	0.411 6 (2)	0.395 8 (2)	0.081 (2)	0.071 (2)	0.101 (2)	0.022 (2)	0.035 (2)	0.037 (2)

atom	*x*	*y*	*z*	*B*, Å^2	atom	*x*	*y*	*z*	*B*, Å^2
O_1	0.6208 (4)	0.5521 (3)	0.2555 (3)	4.5 (1)	C_{14}	0.3154 (7)	−0.0748 (5)	0.4857 (5)	4.7 (2)
O_2	0.4808 (4)	0.5417 (3)	0.3249 (3)	4.3 (1)	C_{15}	0.2771 (7)	−0.0230 (5)	0.5261 (5)	5.2 (2)
O_3	0.5171 (5)	0.4201 (4)	0.2266 (4)	6.3 (2)	C_{16}	0.3044 (6)	0.0512 (5)	0.5198 (5)	4.0 (2)
C_1	0.7111 (8)	0.5443 (6)	0.2335 (6)	6.7 (3)	C_{17}	0.5082 (5)	0.1783 (4)	0.4066 (4)	2.8 (2)
C_2	0.7692 (9)	0.4989 (7)	0.2739 (7)	7.9 (3)	C_{18}	0.5755 (6)	0.2197 (5)	0.4351 (5)	3.7 (2)
C_3	0.4275 (7)	0.5349 (6)	0.3866 (6)	5.6 (2)	C_{19}	0.6530 (6)	0.2327 (5)	0.3949 (5)	4.5 (2)
C_4	0.4154 (8)	0.4586 (7)	0.4072 (6)	6.8 (3)	C_{20}	0.6604 (7)	0.2014 (5)	0.3293 (5)	4.7 (2)
C_5	0.3086 (5)	0.2122 (4)	0.4047 (4)	2.6 (2)	C_{21}	0.5929 (6)	0.1607 (5)	0.3017 (5)	4.3 (2)
C_6	0.2203 (6)	0.1923 (4)	0.4152 (4)	3.5 (2)	C_{22}	0.5144 (6)	0.1478 (4)	0.3398 (4)	3.1 (2)
C_7	0.1524 (6)	0.2281 (5)	0.3791 (5)	4.5 (2)	C_{23}	0.4058 (5)	0.2160 (4)	0.5446 (4)	2.7 (2)
C_8	0.1757 (6)	0.2830 (5)	0.3320 (5)	4.4 (2)	C_{24}	0.3966 (6)	0.2909 (5)	0.5417 (4)	3.6 (2)
C_9	0.2650 (6)	0.3023 (5)	0.3208 (5)	4.4 (2)	C_{25}	0.3987 (6)	0.3297 (5)	0.6046 (5)	4.0 (2)
C_{10}	0.3335 (6)	0.2666 (5)	0.3584 (4)	3.6 (2)	C_{26}	0.4110 (6)	0.2948 (5)	0.6668 (5)	4.3 (2)
C_{11}	0.3706 (5)	0.0667 (4)	0.4716 (4)	2.8 (2)	C_{27}	0.4208 (6)	0.2199 (5)	0.6682 (5)	4.0 (2)
C_{12}	0.4130 (6)	0.0138 (5)	0.4301 (5)	3.7 (2)	C_{28}	0.4180 (5)	0.1798 (4)	0.6066 (4)	3.1 (2)
C_{13}	0.3829 (7)	−0.0587 (5)	0.4386 (5)	4.9 (2)					

[a] The form of the anisotropic thermal parameter is $\exp[-(\beta(1,1)^*h^2 + \beta(2,2)^*k^2 + \beta(3,3)^*l^2 + \beta(1,2)^*hk + \beta(1,3)^*hl + \beta(2,3)^*kl)]$.

Table III. Selected Distances (Å) and Selected Angles (Deg)

atom	atom	dist	atom	atom	dist
Tc	S_1	2.283 (2)	S_2	C_4	1.841 (9)
Tc	S_2	2.297 (2)	O_1	C_1	1.429 (9)
Tc	O_1	1.963 (4)	O_2	C_3	1.435 (9)
Tc	O_2	1.936 (4)	C_1	C_2	1.438 (11)
Tc	O_3	1.662 (5)	C_3	C_4	1.478 (11)
S_1	C_2	1.848 (10)			

atom 1	atom 2	atom 3	angle	atom 1	atom 2	atom 3	angle
S_1	Tc	S_2	86.09 (7)	O_2	Tc	O_3	112.0 (2)
S_1	Tc	O_1	83.8 (1)	Tc	S_1	C_2	101.9 (3)
S_1	Tc	O_2	138.1 (1)	Tc	S_2	C_4	96.3 (3)
S_1	Tc	O_3	109.7 (2)	Tc	O_1	C_1	117.9 (4)
S_2	Tc	O_1	141.8 (2)	Tc	O_2	C_3	123.0 (4)
S_2	Tc	O_2	83.6 (1)	O_1	C_1	C_2	118.5 (8)
S_2	Tc	O_3	109.4 (2)	S_1	C_2	C_1	108.2 (7)
O_1	Tc	O_2	79.8 (2)	O_2	C_3	C_4	112.0 (6)
O_1	Tc	O_3	108.7 (2)	S_2	C_4	C_3	108.2 (6)

Å) or **3** (0.791 (3) Å). It has been proposed[10] that the steric demands of the oxo—oxygen in dichloro[hydrotris(1-pyrazolyl)borato]oxotechnetium(V) (**4**) cause the cis ligands to bend away from the Tc═O moiety in the compound. If such an explanation were invoked to explain the relatively short metal-to-basal plane distance in **1**, it might be expected that the O_3–Tc–$O_{1,2}$(av) angle would be significantly smaller than the O_3–Tc–$S_{1,2}$(av) angle. This is not so. The average angles are 110.4 (2) and 109.6 (2)°, respectively. Indeed, O_3–Tc–O_2 is the largest angle of the set. The average O–Tc–S angle in the $TcOS_4$ core of **3** is 110.0 (3)°, and in **2** it is 109.3 (4)°. It can be concluded that the short Tc-to-basal plane distance in **1** is entirely due to the relative Tc–S and Tc–O(ligand) bond lengths and not to sterically induced bond angle deformation.

Although the cis form of **1** was isolated, there is no a priori reason to doubt the existence of the trans isomer. A similar situation occurred for **3**; the cis isomer was isolated, but the trans isomer could be detected by NMR in the unfractionated reaction product. Complex **1** has a moderately intense band in its optical spectrum (λ_{max}(MeCN) = 357 nm; ϵ = 2770 L mol^{-1} cm^{-1}) and a much weaker one (λ_{max} = 525 nm, ϵ = 180 L mol^{-1} cm^{-1}). Any bands at shorter wavelengths are obscured by the absorptions of the tetraphenylarsonium ion. The more intense band has position and extinction coefficient similar to the principle features in the spectra of **2** and **3** and is most likely due to sulfur-to-metal charge-transfer absorption. The weaker band by virtue of its position and intensity may be a d–d transition. The infrared spectrum of **1** (KBr pellet) exhibits a strong band at 948 cm^{-1}, with a weaker, poorly resolved shoulder at 935 cm^{-1} which can be attributed to the technetium–oxo stretching mode (the splitting probably results from a solid-state effect).

The isolation of **1** demonstrates the ease with which the oxotechnetium(V) core is formed during the aerobic reduction of pertechnetate and that the TcO^{3+} core can be stabilized by donors other than four bischelated sulfur atoms. This enlarges the scope of potential ligands for rationally designed radiopharmaceuticals.

Acknowledgment. Financial support from the National Institutes of Health is gratefully acknowledged.

Registry No. **1**, 76584-36-6.

Supplementary Material Available: A table of observed and calculated structure factors (15 pages). Ordering information is given on any current masthead page.

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Adiabatic Potential Surface of the Hexafluorocupric Ion: Contribution to the Stereochemistry of Copper(II) Complexes

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Received July 21, 1980

The statistical analysis of X-ray structural data for Cu(II) complexes with certain chromophores, stimulated largely by the earlier works of Hathaway and co-workers,[1-3] yields some

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0020-1669/81/1320-1618$01.25/0