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Oxorhenium mixed-ligand complexes with the 2,6-dimercaptomethylpyridine ligand. Crystal structure of [2,6-dimercaptomethylpyridinato][*p*-methoxybenzenethiolato]oxorhenium(V)

Berthold Nock [a], Hans-Jürgen Pietzsch [b], Francesco Tisato [c], Theodosia Maina [a], Peter Leibnitz [d], Hartmut Spies [b], E. Chiotellis [a,*]

[a] *Institute of Radioisotopes-Radiodiagnostic Products, National Centre for Scientific Research 'Demokritos', PO Box 60228, 15310 Ag. Paraskevi, Athens, Greece*

[b] *Institut für Bioanorganische und Radiopharmazeutische Chemie, Forschungszentrum Rossendorf, PF 510119, D-01314 Dresden, Germany*

[c] *Istituto di Chimica e Tecnologie Inorganiche e dei Materiali Avanzati, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35020 Padua, Italy*

[d] *Bundesanstalt für Materialforschung, Rudower Chaussee 5, D-12489 Berlin, Germany*

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Abstract

Two novel oxorhenium complexes containing the 2,6-dimercaptomethylpyridine ligand were synthesized and characterized by classical methods of analysis. The [2,6-dimercaptomethylpyridinato][*p*-methoxybenzenethiolato]oxorhenium complex **1**, was produced by simultaneous action of equimolar quantities of 2,6-dimercaptomethylpyridine and *p*-methoxybenzenethiol on the precursor $[(n\text{-}C_4H_9)_4N][ReOCl_4]$ in EtOH. As revealed by spectroscopic data as well as X-ray structure analysis, complex **1** adopts a distorted square pyramidal geometry around the metal with the SNS/S donors forming the basal plane and the oxygen occupying the apex of the pyramid. When the same tridentate ligand reacts with $[(n\text{-}C_4H_9)_4N][ReOCl_3(PO)]$ (PO = *o*-diphenylphosphinophenolato) as a precursor, complex **2a**, [2,6-dimercaptomethylpyridinato][*o*-diphenylphosphinophenolato]-oxorhenium, is obtained. The latter is a six-coordinate rhenium species to which the distorted octahedral geometry is assigned, according to the analytical findings. In this case, the SNS/P donors occupy the equatorial plane and the two oxygen atoms the apices of the distorted octahedron positioned *trans* to each other.

Keywords: Oxorhenium complexes; Mixed ligand complexes; Crystal structures

1. Introduction

The recent spectacular growth of technetium and rhenium chemistry reflects the continuously expanding application of important radionuclides of these elements in Nuclear Medicine either for routine diagnostic scintigraphic imaging (^{99m}Tc) or for cancer radiotherapy ($^{186/188}$Re) [1–6]. Due to the fact that only rhenium possesses stable isotopes, but also because the chemistries of these two Group 7 elements are quite similar — at least as long as no redox reactions are involved —, the design of novel ^{99m}Tc radiopharmaceuticals has been very often based on the development and characterization of the rhenium analogs at macroscopic level [6]. Much effort has been dedicated so far to monooxo $[MO]^{3+}$ metal chelates (M = Tc, Re), leading to the development of classical radiopharmaceuticals such as ^{99m}Tc–ECD [7] and ^{99m}Tc–HM–PAO [8] agents for brain imaging, or ^{99m}Tc–MAG_3 for the study of renal function [9]. However, the site-directed in vivo imaging or radiotherapy by means of high specificity low capacity target systems (receptors, enzymes etc.) is

* Corresponding author. Tel.: +30-1-6513 793; fax: +30-1-6543 526.

E-mail address: mainathe@mail.demokritos.gr (E. Chiotellis)

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a much more difficult task to accomplish [10,11]. As the demand for new more sophisticated ^{99m}Tc (but also $^{186/188}$Re) probes becomes more pressing, novel chelating systems with improved characteristics for either or both metal nuclides are steadily emerging [9–12].

Our recent work has been largely focused on mixed ligand systems for oxorhenium and oxotechnetium containing primarily the SNS/S or the SSS/S donor atom sets with potential application in the imaging of brain perfusion. These are neutral and lipophilic metal chelates adopting a distorted trigonal bipyramidal or square pyramidal geometry [13–19]. Despite the fact that several examples of such mixed ligand metal chelates coupled to pharmacophore groups, like tropane, ketanserin or *o*-methoxyphenylpiperazine, have been recently proposed for the in vivo mapping of brain receptors [20–24], complications related to their in vivo instability prevent their effective application for such purposes [25–27]. We have recently proposed the use of mixed ligand complexes, wherein the monothiolato coligand of the SNS/S ligand system has been replaced by a bidentate *o*-diphenylphosphinophenolato ligand. Thus, six-coordinate octahedral complexes, instead of five-coordinate ones, form exhibiting a closed coordination shell and, consequently, an increased stability [28].

We report herein on the synthesis and characterization of two novel oxorhenium complexes containing 2,6-dimercaptomethylpyridine as the tridentate ligand. This tridentate ligand, possessing an aromatic nitrogen donor atom, is for the first time studied in relation to the above mixed ligand systems. Thus, the complexes [2,6 - dimercaptomethylpyridinato][*p* - methoxybenzenethiolato]oxorhenium, **1**, and [2,6-dimercaptomethylpyridinato][*o* - diphenylphosphinophenolato]oxorhenium, **2**, complexes are prepared and characterized. Crystal structure analysis of complex **1** is also reported.

2. Experimental

2.1. General

All chemicals were reagent grade and used as such without prior purification. *p*-Methoxythiophenol and 2,6-pyridinedimethanol were purchased from Fluka. The synthesis and characterization of *o*-diphenylphosphinophenol (POH) was performed according to published protocols [29,30]. Rhenium was purchased from Aldrich as $KReO_4$ and was converted to [(n-C_4H_9)$_4$N][$ReOCl_4$] according to published methods [31]. Solvents for high performance liquid chromatography (HPLC) were HPLC grade; they were filtered through membrane filters (0.22 μ, Millipore, Milford/USA) and degassed by helium flux prior to use. Column chromatography was performed on silica gel packing material from Merck. Thin layer chromatography (TLC) was conducted on 0.25 mm silica gel coated aluminium F_{254} sheets from Merck. HPLC analysis was performed on a Waters Chromatograph efficient with a Waters 600 solvent delivery system and coupled to a Waters 996 photodiode array UV detector. The Millennium Software by Waters was applied for controlling the HPLC system and processing the data. For analyses a Lichrospher 100 RP C18 (10 μ, 4.0 mm × 250 mm) column from Merck was eluted at a flow rate of 1 ml min^{-1} MeOH and aqueous or buffer mixtures of varying composition.

IR spectra were recorded on KBr pellets on a Perkin–Elmer 1600 FTIR spectrophotometer in the region 500–4000 cm^{-1} and using polystyrene for reference. Proton, ^{13}C and ^{31}P NMR spectra were recorded on a Bruker AC-200 instrument, using $SiMe_4$ as internal reference (for ^{1}H and ^{13}C) and 85% aqueous H_3PO_4 as external reference (for ^{31}P). Samples were dissolved in deuterated chloroform at a concentration of approximately 1–2%. Elemental analyses for C, H, N and S were conducted on a Perkin–Elmer 2400/II automatic elemental analyzer.

2.2. Synthesis of 2,6-dimercaptomethylpyridine ligand

To a suspension of 2,6-pyridinedimethanol (14.4 g, 0.1 mmol) in Et_2O (100 ml) at 0°C a solution of $SOCl_2$ (15.8 ml, 0.22 mmol) in Et_2O (25 ml) was added within 15 min. After completion of the addition the mixture was allowed to reach ambient temperature and was stirred overnight. The forming precipitate was filtered off and rinsed with Et_2O to afford 2,6-dichloromethylpyridine hydrochloride (Yield: 21.68 g, 100%).

The chloride (5 g, 24 mmol) was reacted with thiourea (4.3 g, 57 mmol) in refluxing EtOH (100 ml) for 15 min. The solvent was expelled under vacuum and the white residue redissolved in H_2O (20 ml). This solution was refluxed with NaOH (3.1 g, 78 mmol) for 2 h under an Ar atmosphere and the pH then adjusted to 8 by addition of 1 N HCl. Extraction in $CHCl_3$ and evaporation of the solvent under vacuum were followed by vacuum distillation affording 2,6-dimercaptomethylpyridine as a pale yellow oil.

Yield: 2.1 g, 50%; B.p.: 84–87°C (0.01 Torr); HRMS (EI, 70 eV) Calc. for $C_7H_9NS_2$: 171.0176. Found: 171.0150; ^{1}H NMR (200 MHz, $CDCl_3$): 2.01 (2H, t, $J = 7.8$ Hz, S–*H*), 3.82 (4H, d, $J = 7.8$ Hz, CH_2SH), 7.20 (2H, d, $J = 7.7$ Hz, 3-*H*), 7.62 (1H, t, $J = 7.7$ Hz, 4-*H*).

2.3. Synthesis of Re(V)O complexes

2.3.1. [2,6-Dimercaptomethylpyridinato]-[p-methoxybenzenethiolato]oxorhenium(V) (1)

A solution of $[(n\text{-}C_4H_9)_4N][ReOCl_4]$ (146.6 mg, 250 μmol) in EtOH (2 ml) was cooled to 0°C. At this temperature a solution of 2,6-dimercaptomethylpyridin (43 mg, 250 μmol) and *p*-methoxybenzenethiol (34 μl, 275 μmol) in $CHCl_3$ was added under stirring. The color of the mixture immediately changed to red. Stirring at 0°C was continued for a further 2 h and then overnight at ambient temperature. The solvent was removed under vacuum and the residue redissolved in a small portion of $CHCl_3$. The resulting red solution was purified over a silica column using $CHCl_3$ as the eluent affording a pure red solution from which a red solid was collected. Crystals suitable for X-ray analysis were obtained by slow evaporation of a CH_2Cl_2/MeOH solution of the product or by standing of such a solution at 2°C overnight.

Yield: 61 mg, 48%; m.p.: 202–204°C; t_R (RP C18 Merck Lichrospher 100 column, 10 μ, 4.6 × 250 mm, 80% MeOH/20% H_2O): 4.58 min; *Anal.* Calc. for $C_{14}H_{14}NO_2ReS_3$: C, 32.88; H, 2.76; N, 2.74; S, 18.77. Found: C, 32.60; H, 2.96; N, 2.56; S, 18.12; IR (KBr, ν/cm^{-1}): 1603, 1561, 1464, 1433, 1023, 968 (s, Re = O); UV–Vis (λ/nm, MeOH/H_2O 80/20) 283, 360; ^1H NMR (200 MHz, $CDCl_3$): 3.86 (3H, s, OCH_3), 4.97 (2H, br, pyr-CH_2–S–ReO), 5.17 (1H, br, pyr-CH_2–S–ReO), 5.53 (1H, br, pyr-CH_2–S–ReO), 6.97 (2H, d, $J = 8.8$ Hz, Ar–*H*), 7.60 (2H, d, $J = 8.8$ Hz, Ar–*H*), 7.80 (2H, br, 3,5-pyr–*H*), 7.97 (1H, t, $J = 7.8$ Hz, 4-pyr-*H*).

2.3.2. [2,6-Dimercaptomethylpyridinato]-[o-diphenylphosphinophenolato]oxorhenium(V) (2a)

By reacting the $[(n\text{-}C_4H_9)_4N][ReOCl_4]$ precursor with an equimolar amount of POH, as described previously [28,32], the emerald $[(n\text{-}C_4H_9)_4N][ReOCl_3(PO)]$ intermediate complex was obtained. This complex (200 mg, 0.24 mmol) was dissolved in CH_3CN and a solution of 2,6-dimercaptomethylpyridine ligand (41.04 mg, 0.24 mmol) in MeOH (10 ml) was added under stirring, whereupon the color of the mixture turned rapidly from emerald to green. The mixture was then refluxed under stirring for 30 min giving an orange-brown solution. The solvent was evaporated to dryness under vacuum and the residue redissolved in a small portion of CH_2Cl_2. The product was purified on a silica gel column using CH_2Cl_2 as the eluent. Two bands were eluted and collected from the column, the major fraction containing a red complex **2a**, and a second minor fraction containing a yellow complex **2b**. By concentrating both fractions to a small volume and by addition of MeOH the products were isolated as pure red and yellow solids, respectively.

For **2a**: Yield: 93.5 mg, 60%; Rf (SiO_2; CH_2Cl_2): 0.10; t_R (Waters Symmetry Shield RP 18 column, 5 μ, 150 × 3.9 mm; 1 ml min^{-1}; A: MeCN, B: 0.1% TFA; 1–10 min 50 to 80% A): 8.41 min; *Anal.* Calc. for $C_{25}H_{21}NO_2PReS_2$: C, 46.29; H, 3.26; N, 2.16; S, 9.88. Found: C, 46.32; H, 3.06; N, 2.32; S, 10.00; IR (KBr, ν/cm^{-1}): 1583, 1456, 1320, 1275, 1097, 1023, 951 (s, ν[Re=O]), 857; UV–Vis (λ/nm, CH_2Cl_2): 313, 399; ^1H NMR (200 MHz, $CDCl_3$, ppm): 5.29 (4H, AB system, pyr-CH_2S), 6.34 (1H, dd, $J = 5.3$ Hz, J_{HP} 3.0 Hz, H_a-PO), 6.65 (1H, t, $J = 5.3$ Hz, H_c-PO), 7.11 (1H, t, $J = 5.3$ Hz, H_b-PO), 7.31 (1H, t, $J = 5.3$ Hz, H_d–PO), 7.43–7.90 (10H, PPh–*H*), 7.72 (2H, d, $J = 7.7$ Hz, 3,5-pyr-*H*), 7.93 (1H, t, $J = 7.7$ Hz, 4-pyr-*H*). ^{13}C NMR (200 MHz, $CDCl_3$, ppm): 53.8 (CH_2–S), 117.0, 119.2, 119.5, 128.5, 131.0, 131.9, 133.4, 133.5, 133.6, 140.8, 153.8 (C_{arom}); ^{31}P NMR (200 MHz, $CDCl_3$, ppm): 13.1 (s). The product is soluble in chlorinated solvents, sparingly soluble in alcohols and insoluble in Et_2O.

For **2b**: Yield: 93.5 mg, 20%; Rf (SiO_2; CH_2Cl_2): 0.05; t_R (Waters Symmetry Shield RP 18 column, 5 μ, 150 × 3.9 mm; 1 ml min^{-1}; A: MeCN, B: 0.1% TFA; 1–10 min 50 to 80% A): 6.63 min; *Anal.* Calc. for $C_{43}H_{36}NO_3P_2ReS_2$: C, 55.66; H, 3.91; N, 1.51; S, 6.90. Found: C, 55.45; H, 3.95; N, 1.47; S, 6.76; IR (KBr, ν/cm^{-1}): 2923, 1583, 1455, 1438, 1299, 1261, 1228, 1096, 947 (s, ν[Re=O]), 908, 854; UV–Vis (λ/nm, CH_2Cl_2) 308, 388; ^1H NMR (200 MHz, $CDCl_3$, ppm): 4.70–5.35 (4H, CH_2S), 5.70–7.82 (31H, H_{arom}); ^{31}P NMR (200 MHz, $CDCl_3$, ppm): 4.4 (d, $J_{PP} = 8$ Hz), 9.6 (d, $J_{PP} = 8$ Hz). The product is soluble in alcohols, sparingly soluble in chlorinated solvents and insoluble in Et_2O.

2.4. X-ray diffraction data and crystal structure determination and refinement for 1

The X-ray data were collected at room temperature (293 K) on a SMART-CCD diffractometer (SIEMENS), using graphite monochromatized Mo Kα radiation ($\lambda = 0.71073$ Å). A summary of the crystallographic data is given in Table 1. The positions of the non-hydrogen atoms were determined by the heavy atom technique. After anisotropic refinement of the positions of these, the hydrogen positions were calculated according to ideal geometries. Empirical absorption corrections were made using psi scans. Most of the calculations were carried out in the SHELXTL system with some local modifications.

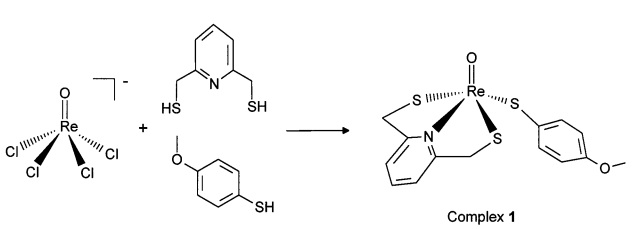
Relevant bond lengths and angles are contained in Table 2. Atomic positional and thermal parameters, full lists of bond lengths and angles, and F_o/F_c values have been deposited as supplementary material.

Table 1
Crystal data and structure refinement for complex **1**

Parameter	Complex **1**
Empirical formula	$C_{14}H_{14}NO_2S_3Re$
Formula weight	510.64
Crystal system	orthorhombic
Space group	$P2_12_12_1$
Unit cell dimensions	
a (Å)	7.249(5)
b (Å)	7.915(4)
c (Å)	28.206(9)
α (°)	90.00
β (°)	90.00
γ (°)	90.00
Volume (Å^3)	1618.4(15)
Z	4
Temperature (K)	293(2)
ρ (g cm^{-3})	2.096
Absorption coefficient (mm^{-1})	7.897
$F(000)$	976
λ(Mo Kα) (Å)	0.71073
Crystal size (mm^3)	$0.54\times0.27\times0.27$
θ-range for data collection	2.67–25.95
Index ranges	$-8\le h\le 0$ $-9\le k\le 0$ $-34\le l\le 34$
Reflections collected	3625
Independent reflections	2949
Goodness-of-fit on F^2	1.064
R [$I>2\sigma(I)$]	$R_1=0.0334$, $wR_2=0.0870$
R (all data)	$R_1=0.0472$ $wR_2=0.2186$

Table 2
Selected bond length (Å) and angles (°) for complex **1**

Re–O1	1.692(7)
Re–N	2.106(8)
Re–S3	2.279(3)
Re–S1	2.286(3)
Re–S2	2.290(3)
O1–Re–N	106.3(4)
O1–Re–S3	111.6(3)
N–Re–S3	81.7(3)
O1–Re–S1	111.0(3)
N–Re–S1	80.1(2)
S3–Re–S1	136.87(12)
O1–Re–S2	107.3(3)
N–Re–S2	146.1(2)
S3–Re–S2	89.63(10)
S1–Re–S2	84.37(11)



Scheme 1. Synthesis of complex **1**.

3. Results and discussion

In this work oxorhenium mixed ligand complexes containing the 2,6-dimercaptomethylpyridine ligand have been synthesized and characterized by classical analytical methods. Preparation and analytical data of 2,6-dimercaptomethylpyridine are also reported.

Thus, complex **1** was obtained in good yields by reaction of equimolar amounts of 2,6-dimercaptomethylpyridine and *p*-methoxybenzenethiol with the $[(n\text{-}C_4H_9)_4N][ReOCl_4]$ precursor, as shown in Scheme 1. The product was purified on a silica column and crystallized by slow evaporation from a CH_2Cl_2–MeOH solution. Given that the three thiolate groups of the tridentate and the monodentate ligand are deprotonated upon coordination, complex **1** is a neutral five-coordinate species. Formation of complex **1** has been established by elemental analysis, IR, UV–Vis and NMR spectroscopies. The strong band at 965 cm^{-1} is assigned to the ν[Re=O] stretching vibration and is consistent with that reported for several other well-characterized monooxo rhenium complexes [13–16,18,19,28,31,32]. The UV–Vis spectrum reveals a maximum at 360 nm, characteristic of Re(V)O–S charge transfer band(s), as reported for analogous oxorhenium species [13–16,18,19].

Upon coordination the proton signals of the thiol groups disappear from the NMR spectral pattern, whereas the other signals experience a remarkable downfield shift, as expected for the strong acid character of the $[ReO]^{3+}$ moiety. In addition, the methylene protons of the tridentate ligand become diastereotopic because of the asymmetry introduced in the molecule by the oxo group (exo and endo protons) and by some steric constraints,which place these protons in slightly different magnetic environments.

A crystal suitable for X-ray structure analysis was obtained for complex **1** and relevant crystallographic data are summarized in Table 1. As shown in the ORTEP diagram of Fig. 1, complex **1** adopts the usual distorted square-pyramidal arrangement of the four donor atoms (SNS/S) around the $[Re{=}O]^{3+}$ core. The tridentate ligand, representing a novel framework of donor atoms capable of forming '3 + 1' mixed-ligand complexes, spans three positions in the basal plane, via the charged thiolate S atoms and the neutral pyridine nitrogen. The fourth position is occupied by the *p*-methoxybenzenethiolate S atom. The Re atom lies above the basal plane towards the O apex (0.83 Å).

In comparison to the Re–N bond lengths observed in the X-ray structures of '3 + 1' mixed-ligand 'SN(alkyl)S' complexes [15,18] the Re–N(pyr) distance is significantly shorter by 0.1 Å, due to the aromatic character of the pyridine nitrogen (2.10 Å for **1** vs. 2.21 Å for Ref. [15] and 2.18 Å for Ref. [18]). The distances of the Re–S bonds (2.27–2.29 Å) fall in the usual range

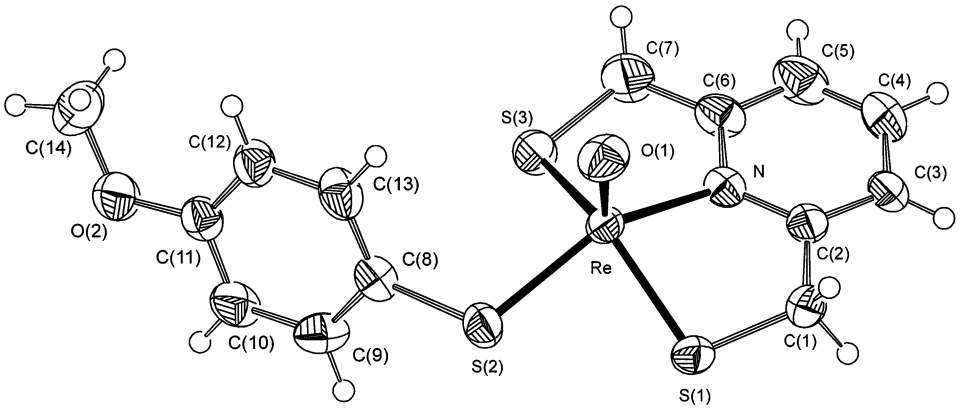
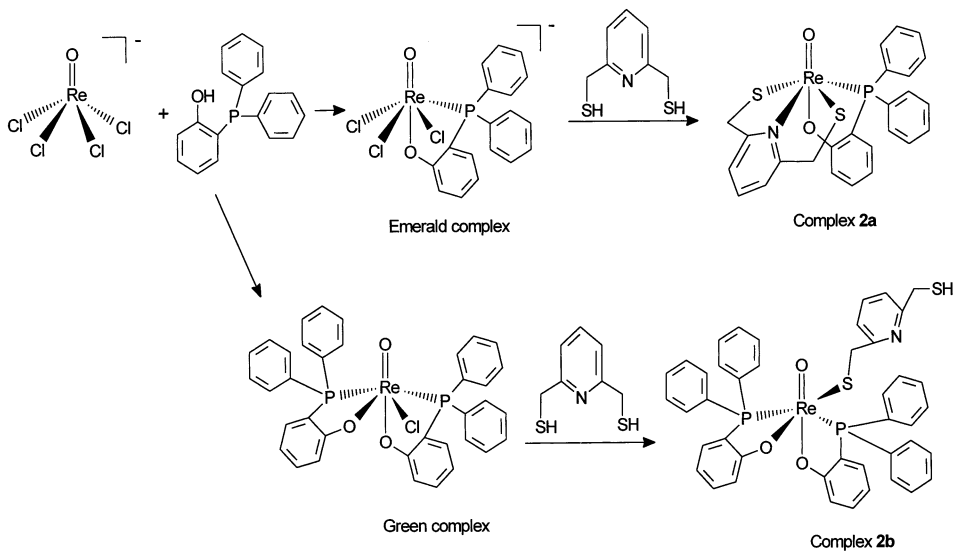


Fig. 1. An ORTEP diagram of complex **1**.



Scheme 2. A two step synthesis of complexes **2a** and **2b**.

previously reported for a series of oxorhenium(V) complexes [13,15,18,19].

Complex **2a**, as depicted in Scheme 2, was obtained by a two step synthesis: (i) equimolar amounts of *o*-diphenylphosphinophenol were reacted with the same precursor $[(n\text{-}C_4H_9)_4N][ReOCl_4]$ affording the emerald intermediate $[(n\text{-}C_4H_9)_4N][ReOCl_3(PO)]$; (ii) the latter was then reacted with 2,6-dimercaptomethylpyridine affording complex **2a** as a red solid. This compound was purified on a silica column and crystallized by slow evaporation from a CH_2Cl_2–MeOH solution. However, it was not possible to grow crystals of sufficient quality for X-ray crystallographic studies. Formation and purity of complex **2a** was established by elemental analysis, IR, UV–Vis and NMR spectroscopies. Complex **2a** is a six-coordinate neutral oxorhenium species, given that the two thiolate groups of the SNS ligand and the hydroxy group of the PO ligand are deprotonated upon coordination to the ReO^{3+} core. The IR spectrum shows an intense band at 951 cm^{-1} corresponding to the Re=O stretching vibration, found in good agreement with that of analogous six-coordinate oxorhenium complexes containing the same PO ligand [28,32]. The UV–Vis spectrum exhibits a maximum at 313, 399 nm, similar to that of similar oxorhenium compounds [28].

A complete ^1H, ^{13}C and ^{31}P NMR analysis confirms the formula assigned to complex **2a**. In detail, the proton spectrum displays the expected AB pattern for the methylene protons of the tridentate ligand centered at 5.29 ppm, along with signals of the pyridine ring deshielded with respect to those of the uncoordinated ligand. The aromatic protons of the phenyl ring interposed between the donors of the PO^- ligand display a four signal pattern consistent with the coordination spanning a position on the equatorial plane (P) and the position *trans* to the oxo linkage (O), as previously

shown by the parent complex $[ReOCl_3(PO)]^-$ [32] and related bis-substituted P,O-oxorhenium compounds [33]. Analogously, the ^{13}C spectrum shows the aliphatic carbon at 53.8 ppm and all of the aromatic signals arising from both the pyridine and arylphosphine in the range 117.0–153.8 ppm. The ^{31}P spectrum exhibits a singlet at 13.1 ppm to be compared with the signal of uncoordinated POH which falls at -31.2 ppm [32].

During the synthesis of the mono-substituted $[ReOCl_3(PO)]^-$ emerald complex, always trace amounts of the bis-substituted $[ReOCl(PO)_2]$ green compound are recovered [32]. The latter reacts also with 2,6-dimercaptomethylpyridine leading to the formation of a minor complex **2b**, as depicted in Scheme 2. It was isolated from a silica column during the purification of the major complex **2a**. Complex **2b** is more hydrophilic as compared to **2a**. The IR spectrum of **2b** reveals a band at 947 cm^{-1} attributed to the ν[Re=O] stretching vibration [28,32]. The formulation of **2b** was assessed by NMR studies. The ^{31}P spectrum clearly indicates the presence of two magnetically unequivalent P nuclei giving a two doublets pattern with coupling constant of 8 Hz, in agreement with a *cis*-P configuration (see Scheme 2). These two doublets are centered at 9.6 and 4.6 ppm, values slightly different from those observed in the same solvent (11.6 and 2.3 ppm) for the parent complex $[ReOCl(PO)_2]$, indicating the substitution of the chloride ligand by the thiolate function of the dimercaptomethylpyridine ligand. The proton spectrum shows two multiplets in the methylene region, along with a series of overlapped multiplets in the aromatic region in the correct 4:31 integration ratio. The coordination of a thiolate group leaving outside a further uncoordinated dangling thiol is precedented [34].

4. Supplementary material

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-136219. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44-1223-336033; e-mail: deposit@ccdc.cam.ac.uk).

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References

[1] I. Steigman, W.C. Eckelman, The Chemistry of Technetium in Medicine, National Academy Press, Washington DC, 1992.
[2] D. Nowotnik, A. Nunn, Drug News Persp. 5 (1991) 174.
[3] S. Jurisson, D. Berning, J. Wei, M. Dangshe, Chem. Rev. 93 (1993) 1137.
[4] W. Volkert, W.F. Goeckeler, G.J. Ehrhardt, A.R. Ketring, J. Nucl. Med. 32 (1991) 174.
[5] J.P. DiZio, R. Fiaschi, A. Davison, A.G. Jones, J.A. Katzenellenbogen, Bioconjugate Chem. 2 (1991) 353.
[6] E.A. Deutsch, K. Libson, J.-L. Vanderheyden, in: M. Nicolini, G. Bandoli, U. Mazzi (Eds.), Technetium and Rhenium in Chemistry and Nuclear Medicine 3, Raven Press, New York, 1990, p. 13.
[7] R.C. Walovitch, T.C. Hill, S.T. Garrity, E.H. Cheesman et al., J. Nucl. Med. 30 (1989) 1892.
[8] R.D. Neirinckx, L.R. Canning, I.M. Riper, D.P. Nowotnik et al., J. Nucl. Med. 28 (1987) 191.
[9] W. Brandau, B. Bubeck, M. Eisenhut, D.M. Taylor, Appl. Radiat. Isot. 39 (1988) 121.
[10] W.C. Eckelman, Eur. J. Nucl. Med. 22 (1995) 249.
[11] R.K. Hom, J.A. Katzenellenbogen, Nucl. Med. Biol. 24 (1997) 485.
[12] W.A. Volkert, in: M. Nicolini, G. Bandoli, U. Mazzi (Eds.), Technetium and Rhenium in Chemistry and Nuclear Medicine 4, SGEditoriali, Padua, Italy, 1995, p. 17.
[13] D.M. Spyriounis, M. Pelecanou, C.I. Stassinopoulou, C.P. Raptopoulou, A. Terzis, E. Chiotellis, Inorg. Chem. 34 (1995) 1077.
[14] M. Papadopoulos, I. Pirmettis, M. Pelecanou, C.P. Raptopoulou, A. Terzis, C.I. Stassinopoulou, E. Chiotellis, Inorg. Chem. 35 (1996) 7377.
[15] M. Pelecanou, I.C. Pirmettis, M.S. Papadopoulos, C.P. Raptopoulou, A. Terzis, E. Chiotellis, C.I. Stassinopoulou, Inorg. Chim. Acta 287 (1999) 142.
[16] I. Pirmettis, M.S. Papadopoulos, S.G. Mastrostamatis, C.P. Raptopoulou, A. Terzis, E. Chiotellis, Inorg. Chem. 35 (1996) 1685.
[17] I.C. Pirmettis, M.S. Papadopoulos, E. Chiotellis, J. Med. Chem. 40 (1997) 2539.
[18] T. Fietz, P. Leibnitz, H. Spies, B. Johannsen, Polyhedron 18 (1999) 1793.
[19] H. Spies, T. Fietz, H.-J. Pietzsch, B. Johannsen, P. Leibnitz, G. Reck, D. Scheller, K. Klostermann, J. Chem. Soc., Dalton Trans. (1995) 2277.
[20] S. Meegalla, K. Plössl, M.-P. Kung, D.A. Stevenson, L.-M. Liable-Sands, A.L. Rheingold, H.F. Kung, J. Am. Chem. Soc. 117 (1995) 11037.
[21] S. Meegalla, K. Plössl, M.-P. Kung, S. Chumpradit, D.A. Stevenson, D. Frederick, H.F. Kung, Bioconjugate Chem. 7 (1996) 421.
[22] B. Johannsen, R. Berger, P. Brust, H.-J. Pietzsch, M. Scheunemann, S. Seifert, H. Spies, R. Syhre, Eur. J. Nucl. Med. 24 (1997) 316.
[23] B. Johannsen, M. Scheunemann, H. Spies, P. Brust, J. Wober, R. Syhre, Nucl. Med. Biol. 23 (1996) 429.
[24] D. Papagiannopoulou, L. Mallo, M. Papadopoulos, I. Pirmettis, T. Maina, B. Nock, A. Leon, E. Chiotellis, [Abstr.] Eur. J. Nucl. Med. 26 (1999) 989.
[25] B. Nock, T. Maina, D. Yannoukakos, I.C. Pirmettis, M.S. Papadopoulos, E. Chiotellis, J. Med. Chem. 42 (1999) 1066.
[26] M. Pelecanou, I.C. Pirmettis, B.A. Nock, M. Papadopoulos, E. Chiotellis, C.I. Stassinopoulou, Inorg. Chim. Acta 281 (1998) 148.
[27] R. Syhre, S. Seifert, H. Spies, A. Gupta, B. Johannsen, Eur. J. Nucl. Med. 25 (1998) 793.

[28] B. Nock, T. Maina, F. Tisato, M. Papadopoulos, C.P. Raptopoulou, A. Terzis, E. Chiotellis, Inorg. Chem. 38 (1999) 4197.
[29] T.B. Rauchfuss, Inorg. Chem. 16 (1977) 2966.
[30] J. Yardley, H. Fletcher, 3rd Synthesis (1975) 244.
[31] G. Rouschias, Chem. Rev. 74 (1974) 531.
[32] C. Bolzati, F. Tisato, F. Refosco, G. Bandoli, A. Dolmella, Inorg. Chem. 35 (1996) 6221.
[33] H. Luo, I. Setyawati, S.J. Rettig, C. Orvig, Inorg. Chem. 34 (1995) 2287.
[34] K.P. Maresca, G.H. Bonavia, J.W. Babich, J. Zubieta, Inorg. Chim. Acta 284 (1999) 252.