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The Crucial Role of the Diphosphine Heteroatom X in the Stereochemistry and Stabilization of the Substitution-Inert $[M(N)(PXP)]^{2+}$ Metal Fragments (M = Tc, Re; PXP = Diphosphine Ligand)

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The nature of the heteroatom X incorporated in the five-membered PXP-diphosphine bridging chain was found to play a primary unit role both in the overall stability and in the stereochemical arrangement of nitrido-containing $[M(N)(PXP)]^{2+}$ metal fragments (M = Tc, Re). Thus, by mixing PXP ligands with labile $[Re(N)Cl_4]^-$ and $Tc(N)Cl_2(PPh_3)_2$ nitrido precursors in CH_2Cl_2/MeOH mixtures, a series of neutral $M(N)Cl_2(PXP)$ complexes (M = Tc, **1**–**5**; M = Re, **8**, **9**) was collected. In the resulting distorted octahedrons, PXP adopted facial or meridional coordination, and combination with halide co-ligands produced three different stereochemical arrangements, that is, *fac*,*cis*, *mer*,*cis*, and *mer*,*trans*, depending primarily on the nature of the diphosphine heteroatom X. When X = NH, *mer*,*cis*-$Tc(N)Cl_2$(PNP1), **1**, was the only isomer formed. Alternatively, when a tertiary amine nitrogen (X = NR; R = CH_3, $CH_2CH_2OCH_3$) was introduced in the bridging chain, *fac*,*cis*-$M(N)Cl_2$(PN(R)P) complexes (M = Tc, **2, 3**; M = Re, **8f**) were obtained. Isomerization into the *mer*,*cis*-$Re(N)Cl_2$(PN(R)P), **8m**, species was observed only in the case of rhenium when the tertiary amine group carried the less encumbering methyl substituent. *fac*,*cis*-$Tc(N)Cl_2$(PSP), **4f**, was isolated in the solid state when X = S, but a mixture of *fac*,*cis*-$Tc(N)Cl_2$(PSP) and *mer*,*trans*-$Tc(N)Cl_2$(PSP), **4m**, isomers was found in equilibrium in the solution state. A similar equilibrium between *fac*,*cis*-$M(N)Cl_2$(POP) (M = Tc, **5f**; M = Re, **9f**) and *mer*,*trans*-$M(N)Cl_2$(POP) (M = Tc, **5m**; M = Re, **9m**) species was detected in POP-containing complexes. The molecular structure of all of these complexes was assessed by means of conventional physicochemical techniques including multinuclear NMR spectroscopy and X-ray diffraction analysis of representative *mer*,*cis*-$Tc(N)Cl_2$(PN(H)P), **1**, *fac*,*cis*-$Tc(N)Cl_2$(PSP), **4f**, and *mer*,*cis*-$Re(N)Cl_2$(PN(Me)P), **8m**, compounds.

Introduction

The recent availability of an efficient method for the production of ^{99m}Tc-species bearing a terminal $[^{99m}Tc(N)]^{2+}$ group[1] has promoted further investigations into the coordination chemistry of nitrido-containing technetium and rhenium compounds. Most of the structurally authenticated nitrido−Tc and −Re complexes are bis-substituted species in which the terminal nitride group is surrounded by two bidentate ligands, as in the case of the complex $Tc(N)(dedc)_2$ (dedc = diethyldithiocarbamate), prepared by Baldas and co-workers in the 1980s.[2] This compound displays a five-coordinate molecular structure having four π-donor dithio-

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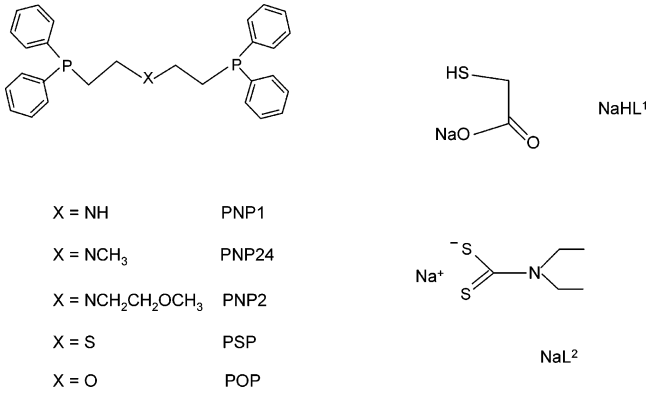
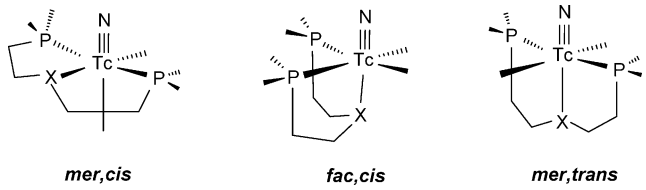


Figure 1. PXP diphosphines and bidentate ligands utilized in this study.

carbamate sulfurs at the base, and the nitrido group at the apex. More recent studies have demonstrated that a mixed donor set comprising a combination of π-donor and π-acceptor atoms around the [Tc(N)] group (i.e., P_2S_2 vs S_4) yielded more stable bis-substituted complexes of the general formula $Tc(N)(PS)_2$ (PS = various dialkylphosphinoethanethiolate or -propanethiolate ligands).[3] By utilizing the concept of the mixed coordinating donor set, we have obtained another class of stable nitrido mixed-chelate complexes of the general formula $[M(N)(S^{\cap}S)(PN(R)P)]^+$ (M = Tc, Re; $S^{\cap}S$ = monoanionic dithiocarbamate and PN(R)P = diphosphine with a tertiary amine group incorporated in the chain).[4] In these pseudo-octahedral compounds, the equatorial coordination of the *cis*-positioned diphosphine phosphorus and of the dithiocarbamate sulfurs is supported by an additional interaction arising from the contact of the diphosphine tertiary amino nitrogen trans to the [M≡(N)] group. This interaction appears to contribute substantially to the overall stability of these classes of mixed nitrido complexes. Otherwise, diphosphines incorporating only methylene units in the chain gave mixtures of species from which the isolation of pure and stable complexes had always failed.[4] Complexes including diphosphines such as the above-mentioned cationic $[M(N)(S^{\cap}S)(PN(R)P)]^+$, prepared at the nca level with ^{99m}Tc, exhibited remarkable inertness toward transchelation with an excess of physiologically relevant cysteine or glutathione[5] and promising biological properties in rats.[6]

Because of the potential application of mixed-chelate nitrido complexes for the development of new radiopharmaceuticals, we thought to investigate the reactivity toward [M≡(N)] cores of other PXP ligands (summarized in Figure 1), which incorporate thioether sulfur (PSP), tertiary amine nitrogen (PNP24), and secondary amine nitrogen (PNP1). This study completes a previous search on the reactivity of

Scheme 1



PNP2 and POP,[7] and compares the stereochemical arrangements of all of the $M(N)Cl_2(PXP)$ prepared.

Here, we report on the reactivity of these PXP diphosphines toward labile $[Re(N)Cl_4]^-$ and $Tc(N)Cl_2(PPh_3)_2$ precursors. The nature of the PXP heteroatom was found crucial for the determination of the stereochemistry of $M(N)Cl_2(PXP)$ complexes when the diphosphine chain was fixed to five. Hence, as sketched in Scheme 1, *fac*,*cis*-$M(N)Cl_2(PXP)$, *mer*,*cis*-$M(N)Cl_2(PXP)$, and *mer*,*trans*-$M(N)Cl_2(PXP)$ species were accessible. Representative examples of each compound category were obtained and characterized through conventional physicochemical techniques including multinuclear NMR and X-ray diffraction analysis of the complexes *mer*,*cis*-$Tc(N)Cl_2(PNP1)$, **1**, *fac*-,*cis*-$Tc(N)Cl_2(PSP)$, **4f**, and *mer*,*cis*-$Re(N)Cl_2(PNP24)$, **8m**.

$M(N)Cl_2(PXP)$ complexes adopting the *fac*,*cis*-arrangement were the ideal intermediate species for further substitution of halides with bidentate π-donor ligands, promoting the formation of mixed-chelate nitrido complexes of the type *fac*-$[M(N)(L^n)(PXP)]^{+/0}$. On the other hand, *mer*,*cis*- and *mer*,*trans*-$M(N)Cl_2(PXP)$ compounds in equilibrium with their corresponding *fac*,*cis*-isomers underwent exchange reactions at a reduced rate, while meridional species which did not experience equilibria with facial isomers did not react at all.

Experimental Section

Caution! ^{99}Tc is a weak β-emitter ($E_\beta = 0.292$ MeV, $t_{1/2} = 2.12 \times 10^5$ years). All manipulations were carried out in laboratories approved for low-level radioactivity using monitored hoods and gloveboxes. When handled in milligram amounts, ^{99}Tc does not present a serious health hazard because common laboratory glassware provides adequate shielding. Bremsstrahlung is not a significant problem due to the low energy of the β-particles. However, normal radiation safety procedures must be used at all times, especially with solid samples, to prevent contamination and inhalation.

Reagents. Technetium as $[NH_4][^{99}TcO_4]$ was obtained from Oak Ridge National Laboratory. Samples were dissolved in water and treated with excess aqueous ammonia and H_2O_2 (30%) at 80 °C prior to use to eliminate residual TcO_2. Solid samples of purified ammonium pertechnetate were obtained by slow evaporation of the solvent with heating at 40 °C. General literature methods were applied to prepare the precursor complexes $[^{99}Tc(N)Cl_2(PPh_3)_2]$,[8] as well as $[n\text{-}Bu_4N][Re(N)Cl_4]$[9] and $Re(N)Cl_2(PPh_3)_2$.[10] Rhenium as a fine metal powder was obtained as a gift from H. C. Starck GmbH, Goslar, Germany. It was first oxidized to perrhenate and then reduced to suitable Re(V) compounds prior to use. Various

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PN(R)P diphosphines (R = H, CH_3, $CH_2CH_2OCH_3$), POP, and PSP ligands were synthesized according to published procedures.[7,11] Common laboratory solvents and other chemicals were used as received.

Physical Measurements. Elemental analyses (C, H, N, S) were performed on a Carlo Erba 1106 elemental analyzer. FT IR spectra were recorded on a Nicolet 510P Fourier transform spectrometer in the range 4000−400 cm^{-1} in KBr mixtures using a Spectra-Tech diffuse-reflectance collector accessory for technetium compounds or on a Mattson 3030 Fourier transform spectrometer in the range 4000−400 cm^{-1} in KBr pellets for rhenium compounds. Proton, ^{13}C, and ^{31}P NMR spectra were collected on a Bruker AMX-300 instrument, using $SiMe_4$ as internal reference (^{1}H and ^{13}C) and 85% aqueous H_3PO_4 as external reference (^{31}P). Mass spectra of selected rhenium compounds (ca. 10^{-6} M methanol solutions) were recorded on a LCQ instrument (Finnigan, Palo Alto, CA). The complexes have been directly injected via a syringe pump at a flow of 5 μL/min.

Syntheses of Technetium Complexes. *mer,cis*-Tc(N)Cl$_2$(PNP1), 1. A suspension of Tc(N)Cl$_2$(PPh$_3$)$_2$ (0.048 g, 0.07 mmol) in dichloromethane (15 mL) was treated with a dichloromethane mixture containing PNP1·HCl (0.046 g, 0.12 mmol) and an equimolar amount of triethylamine (16.0 μL). The mixture was stirred at room temperature for 1 h, giving a clear orange solution, which was then concentrated to 2 mL by a gentle stream of dinitrogen. Addition of diethyl ether (5 mL) afforded a pink-orange solid, which was collected by filtration and washed with ethanol (5 mL) and diethyl ether (2 × 5 mL). The solid is soluble in chlorinated solvents, slightly soluble in acetone and acetonitrile, and insoluble in alcohols. Yield 86%. Anal. Calcd for $C_{28}H_{29}N_2P_2Cl_2Tc\cdot CH_2Cl_2$: C, 49.03; H, 4.40; N, 3.95. Found: C, 49.12; H, 4.47; N, 3.99. IR (KBr, cm^{-1}): 3123 [ν(N−H)] 1435 (s), 1105 (s), 1054 (m) [ν(Tc(N)], 693 (s).

***fac,cis*-Tc(N)Cl$_2$(PXP) (PXP = PNP24, PNP2, PSP, POP).** To a stirred pink suspension of Tc(N)Cl$_2$(PPh$_3$)$_2$ (0.1 mmol) in dichloromethane (15 mL) was added a solution containing a slight excess of the relevant PXP (0.12 mmol) in dichloromethane (5 mL). The mixture was left at room temperature for 1−12 h and slowly became clear yellow (during the reaction, a green color was observed in the case of PSP). Removal of the solvent by slow evaporation gave a yellow solid, which was vigorously stirred in diethyl ether (10 mL) and washed with the same solvent (2 × 5 mL) to afford a pure yellow powder.

***fac,cis*-Tc(N)Cl$_2$(PNP24), 2.** Yield 91%. Anal. Calcd for $C_{29}H_{31}N_2P_2Cl_2Tc$: C, 54.46; H, 4.88; N, 4.38. Found: C, 54.81; H, 4.95; N, 4.30. IR (KBr, cm^{-1}): 1431 (s), 1100 (s), 1059 (m) [ν(Tc(N)], 699 (s).

***fac,cis*-Tc(N)Cl$_2$(PNP2), 3.** See ref 7.

***fac,cis*-Tc(N)Cl$_2$(PSP), 4f.** Yield 64%. Anal. Calcd for $C_{28}H_{28}NSP_2Cl_2Tc$: C, 52.34; H, 4.39; N, 2.18; S, 4.99. Found: C, 52.56; H, 4.37; N, 2.25; S, 4.74. IR (KBr, cm^{-1}): 1424 (s), 1098 (s), 1061 (m) [ν(Tc(N)], 702 (s). The corresponding meridional complex *mer,trans*-Tc(N)Cl$_2$(PSP), **4m**, was characterized only in the solution state via ^{1}H and ^{31}P NMR (see Table 3).

***fac,cis*-Tc(N)Cl$_2$(POP), 5f, and *mer,trans*-Tc(N)Cl$_2$(POP), 5m.** See ref 7.

***fac*-Tc(N)(L^1)(PSP), 6.** To a stirred pink suspension of Tc(N)Cl$_2$(PPh$_3$)$_2$ (0.029 g, 0.04 mmol) in dichloromethane (10 mL) was added a solution containing a PSP (0.019 g, 0.04 mmol) in dichloromethane (3 mL). After being stirred for 1 h at room temperature, the solution was brilliant green. Solid NaHL^1 (0.008 g, 0.04 mmol) was added to the solution, which slowly turned pale yellow. It was stirred at room temperature for an additional 12 h. A white solid (NaCl) was separated by filtration, and the filtrate was reduced in volume to 1 mL by a gentle stream of dinitrogen. Addition of diethyl ether (10 mL) gave a yellow solid, which was filtered off, washed with diethyl ether (2 × 5 mL), and dried under a vacuum pump. Yield 56%. Anal. Calcd for $C_{30}H_{30}NO_2S_2P_2Tc$: C, 54.45; H, 4.57; N, 2.11; S, 9.69. Found: C, 54.71; H, 4.71; N, 2.21; S, 9.51. IR (KBr, cm^{-1}): 1627 (vs, ν(COO)), 1431 (s), 1101 (s), 1060 (m) [ν(Tc(N)], 701 (s).

***fac*-[Tc(N)(L^2)(PSP)][Cl], 7.** To a dichloromethane solution (10 mL) containing **4f** (0.015 g, 0.07 mmol) was added a mixture of NaL^2 (0.008 g, 0.07 mmol) dispersed in ethanol (3 mL) and triethylamine (9.3 μL, 0.07 mmol). The mixture was stirred at room temperature for 2 h. The initially yellow colored solution gradually became pale yellow. A white precipitate was filtered off, and the solvent of the filtrate was eliminated with a gentle stream of dinitrogen. The oily residue was washed with water (3 mL), acetone (5 mL), and diethyl ether (2 × 5 mL). The crude yellow powder was vigorously stirred in diethyl ether (10 mL), and then the solid was filtered off and dried overnight under a dinitrogen stream. Yield 61%. Anal. Calcd for $C_{33}H_{33}N_2S_3P_2TcCl$: C, 52.83; H, 4.43; N, 3.73; S, 12.82. Found: C, 52.81; H, 4.49; N, 3.64; S, 12.62. IR (KBr, cm^{-1}): 1437 (s), 1105 (s), 1068 (m) [ν(Re(N)], 696 (s).

Syntheses of Rhenium Complexes. *fac,cis*-Re(N)Cl$_2$(PNP24), 8f. To a stirred yellow solution of [*n*-Bu$_4$N][Re(N)Cl$_4$] (0.087 g, 0.150 mmol) in dichloromethane (10 mL) was added a slight excess of PNP24 (0.077 g, 0.170 mmol) dissolved in dichloromethane (5 mL). After addition of the ligand, the solution was refluxed for 60 min and its color turned yellow-orange. After cooling, a white solid was filtered off, and the filtrate was concentrated by rotoevaporation to ca. 3 mL. Addition of methanol (10 mL) to the filtrate gave a yellow solid, which was filtered off and washed with diethyl ether (5 mL). It was then dried overnight under a vacuum pump. **8f** is soluble in chlorinated solvents, and insoluble in alcohols and diethyl ether. Yield 84%. Anal. Calcd for $C_{29}H_{31}N_2P_2Cl_2Re$: C, 47.93; H, 4.30; N, 3.86. Found: C, 48.01; H, 4.42; N, 3.79. ^{13}C NMR ($CDCl_3$, ppm): 22.62 (d, −P−(*C*H$_2$−CH$_2$)$_2$N−), 47.22 (s, N−*C*H$_3$), 52.89 (s, P(CH$_2$−*C*H$_2$)$_2$N−), 128.27−132.70 (*C*$_6$H$_5$−P). IR (KBr, cm^{-1}): 1432 (vs), 1102 (s), 1066 (s) [ν(Re(N)], 739 (m), 694 (s), 505 (s). ESI MS (*m*/*z*): 654 [M − 2Cl]$^+$.

Repeated attempts to recrystallize **8f** from dichloromethane/methanol or dichloromethane/acetonitrile solutions afforded a mixture of crystals which were separated by mechanical workup. Yellow needles, which were found to diffract poorly, corresponded to **8f**, whereas orange parallelepipeds were found suitable for X-ray diffraction studies and corresponded to the meridional isomer *mer,cis*-Re(N)Cl$_2$(PNP24), **8m**. Yield 24%. Anal. Calcd for $C_{29}H_{31}N_2P_2Cl_2Re\cdot{}^1/_2CH_3OH$: C, 47.70; H, 4.48; N, 3.80. Found: C, 47.89; H, 4.37; N, 3.87. ^{13}C NMR ($CDCl_3$, ppm): 23.59 (d, −P−(*C*H$_2$−CH$_2$)$_2$N−), 50.67 (s, N−*C*H$_3$), 53.17 (s, P(CH$_2$−*C*H$_2$)$_2$N−), 127.10−131.31 (*C*$_6$H$_5$−P).

***fac,cis*-Re(N)Cl$_2$(POP), 9f, and *mer,trans*-Re(N)Cl$_2$(POP), 9m.** See ref 7.

***fac*-[Re(N)(L^2)(PNP24)][Cl], 10.** See ref 4.

The reactivity of Re(N)Cl$_2$(PPh$_3$)$_2$, analogous to the Tc(N)Cl$_2$(PPh$_3$)$_2$ precursor, toward PXP ligands was found identical to that exhibited by [Re(N)Cl$_4$]$^-$.

X-ray Crystallographic Study. Crystal data and refinement statistics for compound **1**·CH$_2$Cl$_2$, **4f**·MeCN, and **8m**·$^1/_2$MeOH are

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Table 1. Crystallographic Data for **1**·CH_2Cl_2, **4f**·MeCN, and **8m**·$^1/_2$MeOH

	1·CH_2Cl_2	**4f**·MeCN	**8m**·$^1/_2$MeOH
empirical formula	$C_{29}H_{31}Cl_4N_2P_2Tc$	$C_{30}H_{31}Cl_2N_2P_2STc$	$C_{29.5}H_{33}Cl_2N_2O_{0.5}P_2Re$
Mw	709.30	682.47	742.62
cryst syst	monoclinic	monoclinic	monoclinic
space group	$P2_1/n$ (No. 14)	$P2_1/c$ (No. 14)	$C2/c$ (No. 15)
a, Å	12.310(2)	12.161(2)	13.981(3)
b, Å	17.708(3)	10.814(2)	12.127(2)
c, Å	15.197(2)	24.676(5)	18.355(4)
β, deg	109.65(1)	101.93(3)	95.31(3)
V, Å^3	3119.8(8)	3175(1)	3099(1)
Z	4	4	4
ρ (calcd) (g cm^{-3})	1.510	1.428	1.592
μ (Mo Kα) (cm^{-1})	0.929	0.810	4.220
temp (K)	293(2)	293(2)	293(2)
residuals:[a] R, wR_2	0.034, 0.075	0.047, 0.127	0.062, 0.182
GOF	0.823	1.123	1.039

[a] $R = \sum||F_o| - |F_c||/\sum|F_o|$ ("observed" data); w$R_2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{1/2}$ (all data); GOF $= \{\sum[w(F_o^2 - F_c^2)^2]/(n - p)\}^{1/2}$ (n = number of reflections; p = number of refined parameters).

Table 2. Selected Interatomic Distances (Å) and Bond Angles (deg)

(i) **1**·CH_2Cl_2

Tc−Cl(1)	2.421(1)	Tc−P(1)	2.424(1)	Tc−N(1)	1.614(3)
Tc−Cl(2)	2.651(1)	Tc−P(2)	2.429(1)	Tc−N(2)	2.167(3)
Cl(1)−Tc−Cl(2)	89.46(3)	Cl(2)−Tc−P(1)	88.39(3)	P(1)−Tc−N(1)	90.0(1)
Cl(1)−Tc−P(1)	99.08(4)	Cl(2)−Tc−P(2)	83.61(3)	P(1)−Tc−N(2)	81.52(8)
Cl(1)−Tc−P(2)	96.21(3)	Cl(2)−Tc−N(1)	170.2(1)	P(2)−Tc−N(1)	95.3(1)
Cl(1)−Tc−N(1)	100.4(1)	Cl(2)−Tc−N(2)	78.39(7)	P(2)−Tc−N(2)	81.81(7)
Cl(1)−Tc−N(2)	167.82(8)	P(1)−Tc−P(2)	162.66(4)	N(1)−Tc−N(2)	91.8(1)

(ii) **4f**·MeCN

Tc−Cl(1)	2.450(1)	Tc−P(1)	2.445(1)	Tc−N	1.633(5)
Tc−Cl(2)	2.443(1)	Tc−P(2)	2.441(1)	Tc−S	2.808(2)
Cl(1)−Tc−Cl(2)	85.22(5)	Cl(2)−Tc−P(1)	86.95(5)	P(1)−Tc−N(1)	92.2(2)
Cl(1)−Tc−P(1)	160.25(5)	Cl(2)−Tc−P(2)	155.80(6)	P(1)−Tc−S	79.98(5)
Cl(1)−Tc−P(2)	82.25(5)	Cl(2)−Tc−S	77.72(5)	P(2)−Tc−N(1)	94.7(2)
Cl(1)−Tc−S	80.66(5)	Cl(2)−Tc−N(1)	108.8(2)	P(2)−Tc−S	79.87(5)
Cl(1)−Tc−N(1)	107.4(2)	P(1)−Tc−P(2)	98.06(4)	N(1)−Tc−S	169.7(2)

(iii) **8m**·$^1/_2$MeOH[a]

Re−Cl(1)	2.380(3)	Re−P(1)	2.431(2)	Re−N(2)	2.312(8)
Re−Cl(2)	2.440(5)	Re−N(1)	1.93(2)		
Cl(1)−Re−Cl(2)	94.0(1)	Cl(2)−Re−P(1)	94.2(1)	P(1)−Re−N(1)	85.3(5)
Cl(1)−Re−P(1)	99.3(1)	Cl(2)−Re−N(1)	173.6(3)	P(1)−Re−N(2)	80.7(1)
Cl(1)−Re−N(1)	92.4(4)	Cl(2)−Re−N(2)	86.0(1)	N(1)−Re−N(2)	87.6(4)
Cl(2)−Re−N(2)	180.0	P(1)−Re−P(1A)[b]	161.4(1)		

[a] Some caution is required in considering the bond lengths and angles because of the pseudo-symmetry described in the Experimental Section. [b] At $-x$, y, $^1/_2 - z$.

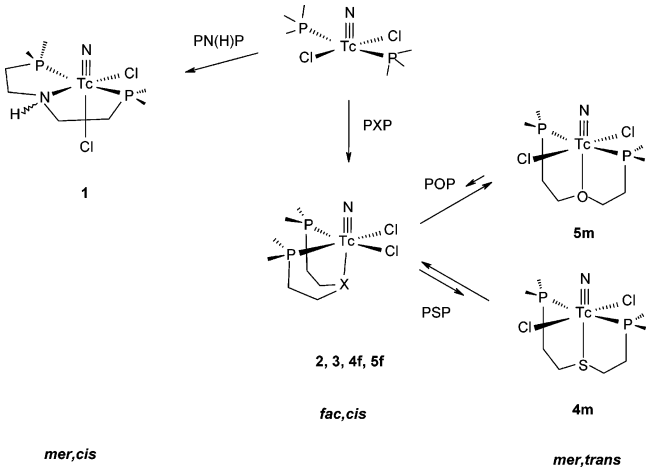
given in Table 1. The crystals have been mounted on the tip of glass fibers encased in epoxy resin for the room-temperature measurements. Data collection for the complexes has been performed on a Nicolet Siemens R3m/V automated diffractometer (oriented graphite monochromator; Mo Kα radiation, $\lambda = 0.71073$ Å). No sign of crystal deterioration has been revealed by monitoring three standard reflections after every 200 measurements.

Data have been collected, up to $2\theta = 50°$ (60° for **8m**·$^1/_2$MeOH), by the $\omega - 2\theta$ scan technique, then corrected for Lorentz-polarization effects and for absorption. The structures have been solved by heavy atom methods, expanded using Fourier techniques, and finally refined against F^2 by the full-matrix least-squares procedure, using the SHELX software package.[12] Totals of 3753, 4225, and 3280 unique reflections, with $I > 2\sigma(I)$, have been observed for **1**·CH_2Cl_2, **4f**·MeCN, and **8m**·$^1/_2$MeOH, respectively. For **1**·CH_2Cl_2 and **4f**·MeCN, hydrogen atoms have been calculated and refined as riding atoms. All non-hydrogen atoms, including solvent molecules, have been refined with anisotropic displacement parameters. Relevant interatomic bond distances and bond angles are given in Table 2 for **1**·CH_2Cl_2 and **4f**·MeCN. Crystals of compound **4f** have been obtained also by recrystallization from both CH_2Cl_2 and $C_2H_4Cl_2$. Such crystals have been found to be made of **4f**·CH_2Cl_2 and **4f**·$C_2H_4Cl_2$, and their crystal data are as follows: **4f**·CH_2Cl_2, monoclinic, $P2_1$, $a = 11.92(1)$, $b = 10.86(1)$, $c = 24.94(2)$ Å, $\beta = 90.15°$, $V = 3230(6)$ Å^3, $Z = 4$, $D_{calcd} = 1.494$ g cm^{-3}; **4f**·$C_2H_4Cl_2$, monoclinic, Pn, $a = 10.850(4)$, $b = 11.949(4)$, $c = 25.349(9)$ Å, $\beta = 90.03°$, $V = 3286(2)$ Å^3, $Z = 4$, $D_{calcd} = 1.496$ g cm^{-3}. Both crystals are highly sensitive toward X-rays, and crystal decay is responsible for the high R-values (R = ca. 0.10) obtained from the refinement procedure. However, the stereochemistry already found in **4f**·MeCN is confirmed altogether in both compounds.

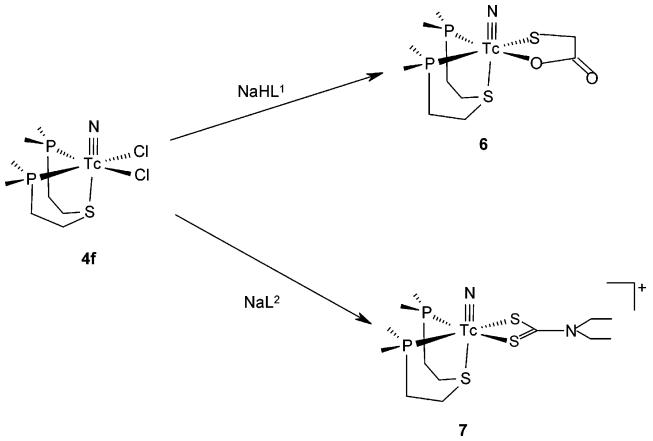
In the case of **8m**·$^1/_2$MeOH, systematic absences could not unambiguously identify the space group; solution and refinement were therefore carried out in both Cc and $C2/c$. The acentric option

(12) Sheldrick, G. M. *SHELXTL/NT*, Version 5.10; Bruker AXS Inc.: Madison, WI, 1999. Sheldrick, G. M. *SHELXL-97, Program for crystal structure refinement*; University of Gottingen: Germany, 1997.

Scheme 2



Scheme 3



was explored, but it gave chemically unreasonable bond lengths (for instance, Re−N(1) distance of 2.49 Å) and caused many large correlation matrix elements (up to 0.84 between the two phosphorus and 0.83 between Cl(2) and N(1) atoms). A more satisfactory refinement was achieved in the centric space group, even if the solution of the structure was relatively difficult, due to the lying of the rhenium atom on the Wyckoff position 4*e* (with the values of *x* (0.00) and *z* (0.25) specified) and, in addition, with *y* of ca. 0.75.

The Re, Cl(1), P(1), and N(2) atoms were located from a Patterson synthesis; a subsequent Fourier synthesis, phased on these atoms, showed the positions of the carbon atoms of the two phenyl rings. The Re, Cl(1), and N(2) atoms are located on a two-fold axis. After three cycles of refinement, in which the occupancy factors of Re, Cl(1), and N(2) were fixed to 0.5 imposed by symmetry, a difference Fourier synthesis gave reliable coordinates for Cl(2) and N(1) atoms lying slightly above and below the rhenium position in the *b* direction. Moreover, the C(2) and C(3) atoms of the chelating diphosphine ligand appeared disordered over two distinct sites. In the subsequent refinement, their occupancy factors were held fixed to 0.5; in fact, attempts to refine individual partial occupancy factors were unsuccessful. Two residual peaks of ca. 2.5 e Å^{-3} were attributed to solvent molecule, MeOH, occupying two related sites near a crystallographic inversion center. The absence of significant (>0.5) matrix correlations and the chemically reasonable results of refinement are consistent with the space groups assigned. All non-hydrogen atoms have been refined with anisotropic displacement parameters.

Relevant bond distances and bond angles for **1**·CH_2Cl_2, **4f**·MeCN, and **8m**·$^1/_2$MeOH are given in Table 2.

Results

Synthesis. Scheme 2 summarizes the reactivity of PXP diphosphines having a five-membered chain toward the technetium precursor Tc(N)Cl$_2$(PPh$_3$)$_2$ in dichloromethane/methanol mixtures. Ligand-exchange reactions involving the secondary aminodiphosphine PNP1 afforded quantitatively the orange-colored *mer*,*cis*-Tc(N)Cl$_2$(PNP1) complex **1**, without contamination of additional isomeric forms.

Reactions involving all of the other diphosphines (PNP2, PNP24, POP, and PSP) gave rise instead to yellow-colored compounds, which were found to adopt the *fac*,*cis* configuration (vide infra). *fac*,*cis*-Tc(N)Cl$_2$(PXP) complexes were stable in the solid state, but some showed equilibria with meridional isomers in solution. In detail, the kinetic compound *fac*,*cis*-Tc(N)Cl$_2$(POP), **5f**, was quantitatively converted into the *mer*,*trans*-Tc(N)Cl$_2$(POP), **5m**, isomer in acetonitrile solution.[7] A mixture of *fac*,*cis*-Tc(N)Cl$_2$(PSP), **4f**, and *mer*,*trans*-Tc(N)Cl$_2$(PSP), **4m**, isomers was instead detected for PSP-containing compounds in acetonitrile and chloroform solutions. From acetonitrile solutions, crystals of the facial isomer **4f** were collected. Conversely, *fac*,*cis*-Tc(N)Cl$_2$(PNP24), **2**, and *fac*,*cis*-Tc(N)Cl$_2$(PNP2), **3**, containing tertiary amine groups in the diphosphine framework did not rearrange into meridional isomers.

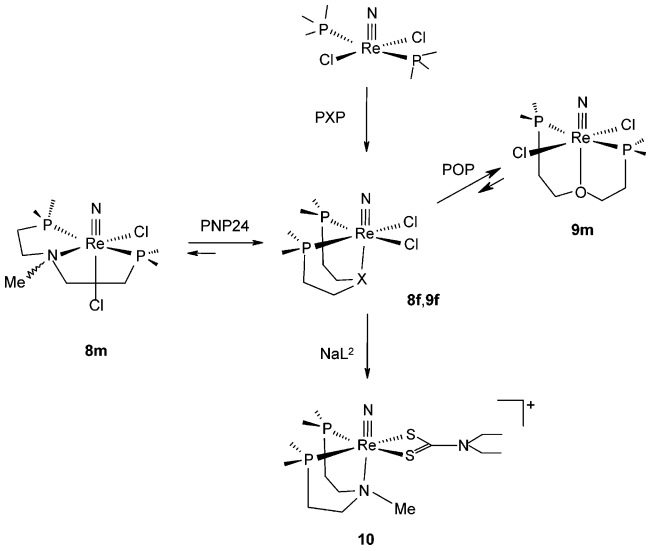
All of the *fac*,*cis*-Tc(N)Cl$_2$(PXP) complexes readily reacted in refluxing dichloromethane/methanol mixtures with bidentate ligands such as mercaptoacetate sodium salt (NaHL^1) and diethyldithiocarbamate sodium salt (NaL^2) to afford mixed ligand complexes of the type *fac*-[Tc(N)(L^n)(PXP)]$^{0/+}$ (**6** and **7**), as illustrated in Scheme 3 for PSP-containing species.

Meridional compounds such as *mer*,*trans*-Tc(N)Cl$_2$(POP) and *mer*,*trans*-Tc(N)Cl$_2$(PSP), in equilibrium with their corresponding *fac*,*cis*-isomers, yielded mixed complexes as well, but at a reduced rate and in lower yield. Otherwise, *mer*,*cis*-Tc(N)Cl$_2$(PNP1), **1**, did not undergo halide substitution under the experimental conditions utilized in the reactions detailed above, indicating that only the facial configuration is the activated form for further substitution.

As sketched in Scheme 4, the reactivity of [Re(N)Cl$_4$]$^-$ or Re(N)Cl$_2$(PPh$_3$)$_2$ precursors with PXP ligands was found to be identical to that exhibited by technetium only in the case of POP. Hence, the kinetic compound *fac*,*cis*-Re(N)Cl$_2$(POP), **9f**, rearranged with the time into the *mer*,*trans*-Re(N)Cl$_2$(POP), **9m**, in acetonitrile solutions. Analogously, the *fac*,*cis*-Re(N)Cl$_2$(PNP24), **8f**, was predominantly produced in the presence of the aminodiphosphine in refluxing dichloromethane solutions. However, **8f** was contaminated by the meridional isomer *mer*,*cis*-Re(N)Cl$_2$(PNP24), **8m**, when the facial compound was recrystallized from acetonitrile/dichloromethane solutions. A mixture of the facial and meridional isomers **8m** and **8f** underwent halide substitution when treated with diethyldithiocarbamate sodium salt to yield the mixed ligand *fac*-[Re(N)(L^2)(PNP24)]$^+$, **10**, complex.

No pure and/or isolable compounds were collected when Re(N)Cl$_2$(PPh$_3$)$_2$ was treated with PSP diphosphines under

Scheme 4



the conditions utilized for the synthesis of analogous technetium compounds (or even using more drastic conditions, i.e., higher boiling solvents, prolonged reaction time, etc.).

Characterization. Elemental analyses, as shown in the Experimental Section, are in good agreement with the proposed formulation. In the IR spectra, nitrido−M(V) complexes exhibit absorptions typical of the coordinated aryldiphosphine ligands at ca. 1100 and 700 cm^{-1}, as well as medium bands in the 1075−1052 cm^{-1} region attributable to ν[M(N)]. Additional vibrations in the region 1627 cm^{-1}, characteristic of the mercaptoacetato group, appear in complex **6**. Electrospray ionization mass spectrometry in the positive ion mode of rhenium compounds shows the molecular ion peak of the cationic mixed complex *fac*-[Re(N)(L^2)(PNP24)]$^+$, **10**, at *m*/*z* 804, whereas neutral intermediate complexes *fac*,*cis*-Re(N)Cl_2(POP), **9f**, and *fac*,*cis*-Re(N)Cl_2(PNP24), **8f**, do not exhibit the $[MH]^+$ ion, but display fragments at *m*/*z* 676 and 654, corresponding to the loss of one and two halides, respectively.

^{31}P NMR spectra of all rhenium and technetium complexes display signals in agreement with diphosphine coordination. They are cumulated in Table 3, along with the signals arising from uncoordinated diphosphines and related compounds reported previously for comparison purposes.[4,7] Despite the diamagnetism exhibited by these nitrido M(V) low-spin d^2 mixed-chelate complexes, ^{31}P NMR signals of technetium species show broad profiles at ambient temperature. Such behavior was previously attributed to the coupling of the ^{31}P nuclei with the quadrupolar ^{99}Tc ($I = {}^9/_2$) center.[8]

In all of the monosubstituted M(N)Cl_2(PXP) compounds **1**−**6**, **8**, and **9**, the ^{31}P signal appears as a singlet according to the magnetic equivalence of the two phosphorus nuclei. Such a signal remains a singlet in the cationic mixed-chelate complexes *fac*-[M(N)(L^2)(PXP)]$^+$ (**7** and **10**) incorporating the symmetrical dithiocarbamate ligand, but it is split into two signals when the dissymmetrical mercaptoacetate ligand is introduced in the coordination sphere, as in *fac*-Tc(N)(L^1)(PSP), **6**.

A detailed analysis of the ^{1}H NMR spectra allows one to distinguish among the three stereochemical forms of the monosubstituted M(N)Cl_2(PXP) complexes (see Scheme 1). The *mer*,*trans*-isomer possesses the highest symmetry in the series: the phenyl substituents at P are all equivalent giving only two multiplets in a narrow ppm window in the aromatic region (Table 3), and geminal protons of the diphosphine methylene chain are equivalent as well, giving only two multiplets (vicinal methylene protons) in the aliphatic region. In *mer*,*cis*- and *fac*,*cis*-isomers, the magnetic equivalence of the phenyl substituents at P and of the bridging geminal protons is removed, according to the *exo* and *endo* orientation, with respect to the nitride group, of the former and the "inside" and "outside" positions of the latter. The associated signals are spread over larger ppm windows both in the aromatic and in the aliphatic regions. In addition, *fac*,*cis*-isomers show a significant upfield shift of the *endo* phenyl protons, engaged in $\pi\angle\pi$ stacking (see Crystallographic Study section), whereas the methylene chain protons in *mer*,*cis*-isomers experience a remarkable downfield shift.

Description of the Structure 1·CH_2Cl_2. The molecular structure of the complex *mer*,*cis*-Tc(N)Cl_2(PNP1), **1**, together with the selected numbering scheme, is drawn in Figure 2. The environment around Tc is distorted octahedral, the dihedral angle between the two triangular faces defined by P(1), N(1), N(2) and Cl(1), P(2), Cl(2) measuring 12.5° instead of 0°, that is, the ideal value for a regular octahedron. The donating atoms in the equatorial plane are those of the diphosphine P(1), N(2), and P(2), and Cl(1). The two phosphorus atoms (trans to each other) are 0.05 Å above the equatorial plane, whereas the chlorine and the nitrogen atoms are below it by −0.04 and −0.06 Å, respectively. The Tc center, instead, is 0.19 Å above the plane, toward N(1). Upon coordination, the chelating diphosphine ligand forms two five-membered rings. Both of them assume an envelope (C_s) conformation, the largest torsion angles being across C(1)−C(2), C(2)−N(2) (−50.7° and 54.8°, respectively), and C(3)−C(4), C(3)−N(2) (54.3° and −54.4°, respectively), a situation occurring also in the structure of **4f**·MeCN described below.

With respect to the phosphine ligand, the two phenyl rings bound at either P(1) and P(2) are virtually orthogonal to each other, again, a situation found also in **4f**·MeCN. The rings bonded at P(1) and P(2) define dihedral angles of 88.0° and 79.0°, respectively. The Tc−Cl(2) distance (2.651(1) Å) is remarkably long. This is due to the trans influence of the N(1) nitrido ligand and is in agreement with the data available in the Cambridge Structural Database.[13]

Description of the Structure 4f·MeCN. The solid-state structure of **4f**·MeCN and the numbering scheme employed are depicted in Figure 3. Also, in this compound, as in **1**·CH_2Cl_2 above, the environment around Tc appears to be distorted octahedral. However, the size of the distortion is smaller than that found in the previous case. The dihedral angle between the two triangular faces P(1), N(1), N(2) and

(13) Allen, F. H. *Acta Crystallogr.* **2002**, *B58*, 380−388; Cambridge Structural Database (Version 5.25 of November 2003).

Table 3. ^{1}H and ^{31}P NMR Data of PXP Diphosphines and Related Technetium and Rhenium Complexes

		^{1}H ppm		
compound	^{31}P ppm	aromatic	diphosphine chain	other
PNP1·HCl	−20.0 (s)	7.40−7.28 (20H)	2.94 (m, 4H) 2.57 (m, 4H)	9.94 (bs, 2H; >N*H*$_2$Cl)
PNP24	−21.5 (s)	7.41−7.30 (20H)	2.48 (m, 4H) 2.14 (m, 4H)	2.24 (s, 3H; N−C*H*$_3$)
PNP2	−21.5 (s)	7.40−7.30 (20H)	2.60 (m, 4H) 2.07 (m, 4H)	3.26 (t, 2H; O−C*H*$_2$−) 3.20 (s, 3H; O−C*H*$_3$) 2.59 (m, 2H; N−C*H*$_2$−)
PSP	−18.8 (s)	7.41−7.24 (20H)	2.55 (m, 4H) 2.27 (m, 4H)	
POP	−24.1(s)	7.43−7.28 (20H)	3.49 (m, 4H) 2.31 (m, 4H)	
mer,*cis*-Tc(N)Cl$_2$(PNP1), **1**	30.1 (bs)	8.00 (m, 8H) 7.45 (m, 12H)	3.65 (m, 2H) 3.06 (m, 4H) 2.64 (m, 2H)	5.45 (t, 1H; N−*H*)
fac,*cis*-Tc(N)Cl$_2$(PNP24), **2**	36.4 (bs)	7.93−6.88 (5m, 20H)	3.05−2.56 (8H)	2.33 (s, 3H; N−C*H*$_3$)
fac,*cis*-Tc(N)Cl$_2$(PNP2), **3**	35.5 (bs)	7.91−6.85 (4m, 20H)	3.52−2.53 (8H)	3.32 (t, 2H; O−C*H*$_2$−) 3.24 (s, 3H; O−C*H*$_3$) 2.67 (m, 2H; N−C*H*$_2$−)
fac,*cis*-Tc(N)Cl$_2$(PSP), **4f**	38.7 (bs)	7.86−6.87 (4m, 20H)	3.22−2.73 (8H)	
mer,*trans*-Tc(N)Cl$_2$(PSP), **4m**	44.8 (bs)	7.99 (m, 8H) 7.42 (m, 12H)	3.67−2.65 (8H)	
fac,*cis*-Tc(N)Cl$_2$(POP), **5f**	23.6 (bs)	7.98−6.87 (4m, 20H)	4.21−2.89 (8H)	
mer,*trans*-Tc(N)Cl$_2$(POP), **5m**	31.2 (bs)	7.87 (m, 8H) 7.37 (m, 12H)	3.71−2.51 (8H)	
fac-Tc(N)(L^1)(PSP), **6**	35.2 (bs) 27.0 (bs)	7.97−6.89 (20H)	3.37−2.42 (8H)	3.44 (dd, 2H; S−C*H*$_2$−)
fac-[Tc(N)(L^2)(PSP)][Cl], **7**	36.7 (bs)	7.94−6.95 (20H)	4.08−2.96 (8H)	3.71 (m, 4H); 1.23 (t, 6H) (>N−C*H*$_2$−C*H*$_3$)
fac,*cis*-Re(N)Cl$_2$(PNP24), **8f**	19.3 (s)	7.94−6.86 (5m, 20H)	3.15−2.72 (8H)	2.30 (s, 3H; N−C*H*$_3$)
mer,*cis*-Re(N)Cl$_2$(PNP24), **8m**	7.5 (s)	8.20−7.38 (20H)	3.07−3.73 (8H)	2.61 (s, 3H; N−C*H*$_3$)
fac,*cis*-Re(N)Cl$_2$(POP), **9f**	16.9 (s)	7.96−6.89 (4m, 20H)	4.34−2.86 (8H)	
mer,*trans*-Re(N)Cl$_2$(POP), **9m**	25.5 (s)	7.90 (m, 8H) 7.38 (m, 12H)	3.72 (m, 4H) 2.91 (m, 4H)	
fac-[Re(N)(L^2)(PNP24)][Cl], **10**	18.8 (s)	7.95−6.96 (20H)	3.56−2.86 (8H)	2.09 (2, 3H; >N−C*H*$_3$); 3.70 (m, 4H), 1.28 (t, 6H) (>N−C*H*$_2$−C*H*$_3$)

Cl(1), S, Cl(2) is 5.8°, instead of the ideal value of 0°. The equatorial positions are occupied by P(1), P(2), Cl(1), and Cl(2); the four atoms deviate from the mean equatorial plane by 0.03, −0.03, 0.03, and −0.03 Å, respectively.

The deviation of the Tc center is greater than in **1**·CH_2Cl_2. The metal is above the equatorial plane, toward N, by 0.44 Å. As reminded above, the chelating ligand forms, upon coordination, two five-membered rings, notably, Tc−P(1)−C(1)−C(2)−S and Tc−P(2)−C(4)−C(3)−S. Both of them assume an envelope (C_s) conformation, where the largest torsion angles are those across the C(1)−C(2) and C(3)−C(4) bonds (57.3° and 60.5°, respectively). The equatorial plane, instead, makes dihedral angles of 95.4° and 88.0° with the Tc−P(1)−C(1)−C(2)−S and Tc−P(2)−C(4)−C(3)−S rings, respectively.

An effective π-stacking intramolecular interaction is operating between two phenyl rings. The distance between the centroids of these rings is 3.64 Å. The two rings are virtually parallel, the dihedral angle between them being only 1.6°, whereas the twist angle τ is 15.4°. The torsional twist angle τ is defined as the C(5)---X_A---X_B---C(17) torsion angle, where X_A and X_B are the two centroids. Besides, the phenyl rings at P(1) are roughly perpendicular (dihedral angle of 81.9°), and similarly those at P(2) are virtually normal to each other (dihedral angle of 94.4°). Again, because of the trans influence of the nitrido ligand, the Tc−S distance (2.808(2) Å) is abnormally long.

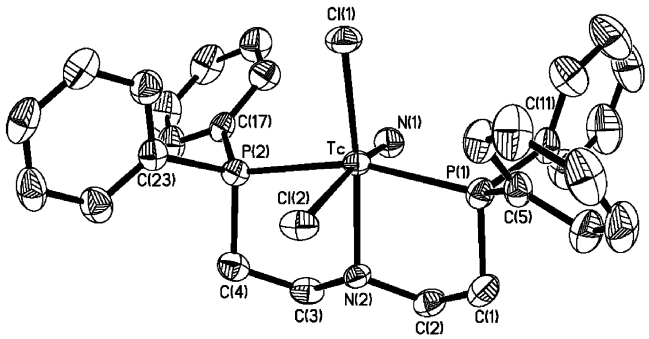


Figure 2. ORTEP view of **1**. Essential atom numbering scheme and displacement ellipsoids (at the 40% probability level) are shown. Hydrogen atoms and CH_2Cl_2 solvent molecule are omitted for clarity.

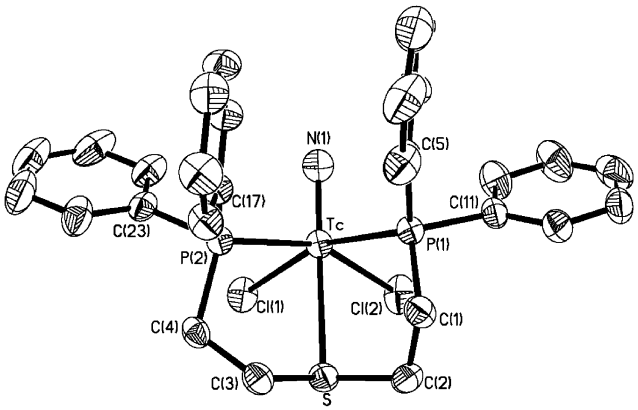


Figure 3. ORTEP view of **4f**. Essential atom numbering scheme and displacement ellipsoids (at the 40% probability level) are shown. Hydrogen atoms and MeCN solvent molecule are omitted for clarity.

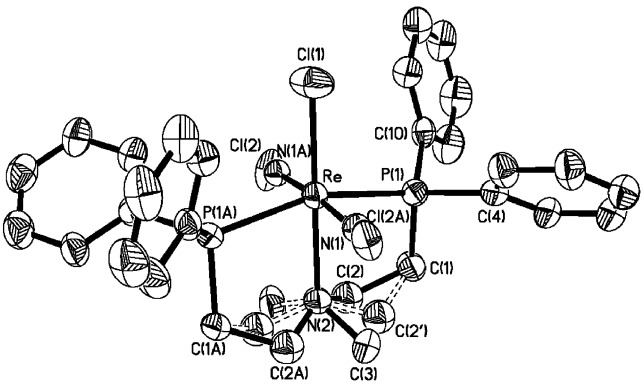


Figure 4. ORTEP view of **8m**. Essential atom numbering scheme and displacement ellipsoids (at the 40% probability level) are shown. Dashed solid bond type is used for the second orientation of the ethylene bridge. Hydrogen atoms and $^1/_2$MeOH solvent molecule are omitted for clarity.

Description of the Structure 8m·$^1/_2$MeOH. The molecular structure of the complex **8m**·$^1/_2$MeOH, together with the selected numbering scheme, is drawn in Figure 4. The latter shows the similarity with the complex **1**·CH_2Cl_2, above-described, but for the replacement of the hydrogen atom bound to N(2) with a methyl group. Again, the coordination environment around the metal is distorted octahedral; the deviation from ideality, measured by the angle between the triangular faces of the octahedron, is 9.6°. The donating set in the equatorial plane is P(1), P(1A), Cl(1), and N(2), and, because of symmetry, all such atoms, along with the rhenium, lie exactly in the plane.

The presence of a second orientation for the ethylene bridge allows the chelating ligand to form in this molecule four five-membered rings. All of the rings assume an envelope (C_s) conformation, in which the atoms "at the flap" are C(2), C(2′A) and C(2A), C(2′), respectively. As expected, the dihedral angles in these five-membered rings show the same values, the largest being those across C(1)−C(2), C(2)−N(2), −45.7° and 55.3°, respectively, (corresponding to C(1A)−C(2A), C(2A)−N(2)), and C(1)−C(2′A), C(2′A)−N(2), 59.7° and −50.8°, respectively. The phenyl rings bound at either P(1) and P(1A) are, again, roughly perpendicular to each other, defining dihedral angles of 81.1° and 98.9°.

The difficulties faced in the refinement and discussed in the Experimental Section do not allow a thorough discussion about bond distances and angles in the rhenium coordination environment. Most of the values found do not appear unusual, anyway, except for the abnormal Re−N(1) distance of 1.93(2) Å (Table 2). Such an unrealistic value is an artifact arising from the very cumbersome refinement of the atomic positions of the Re, N(1), and Cl(2) atoms.

Discussion

Tertiary phosphines are known to be appropriate ligands for technetium and rhenium compounds, as demonstrated by the extensive literature in this field appeared since the 1970s.[14] Following the pioneering investigation of Chatt and co-workers[15] on phosphine rhenium complexes, this chemistry has gained further interest with the design of phosphine technetium compounds potentially useful in nuclear medicine.[16] Efforts in this direction have eventually produced the radiodiagnostic agent [^{99m}Tc-tetrofosmin], a dioxo-Tc(V) species containing two alkyl-substituted diphosphines, currently utilized in the clinical practice to visualize the myocardial district in humans.[17]

Arylphosphine technetium and rhenium complexes are usually arranged to place the phosphine donors in a reciprocal trans configuration to maximize phosphine σ-donor/π-acceptor properties and to minimize steric constraints.[18,19] This behavior is illustrated in common starting materials such as octahedral *trans*-$M^{IV}Cl_4(PPh_3)_2$, *mer*,*trans*-$Re^V(O)Cl_3(PPh_3)_2$, and *mer*,*trans*-$M^V(NPh)Cl_3(PPh_3)_2$ and is confirmed in five-coordinate nitrido-containing complexes *trans*-$M^V(N)Cl_2(PPh_3)_2$. In the latter, the strong donating property of the nitride group induces severe distortions in their square pyramidal (sp) geometry, generating remarkably wide N≡M−Y angles[18,19] (Y = equatorial ligand donor; values much wider than ideal 90°) and, consequently, heavy deviation of the P−M−P linearity. The introduction of additional steric constrains generated by the denticity of functionalized phosphines such as bidentate phosphinothiolate (PS) cause rearrangement of sp into trigonal bipyramidal (tbp) geometries in symmetrical $M(N)(PS)_2$ species,[3] without affecting the *trans*-P coordination. The *trans*-P fashion is retained also in $M(N)Cl_2(POOP)$[20] (POOP = 1,8-bis(diphenylphosphino)-3,6-dioxaoctane) and $M(N)Cl_2(PNP7)$[21] (PNP7 = bis[(2-diphenylphosphino)propyl]methoxyethylamine) complexes, which incorporate diphosphines with long bridging chains (eight-membered and seven-membered chain including the heteroatom(s), respectively), again indicating that a *trans*-P arrangement is strongly preferred when the diphosphine framework does not induce heavy steric constrains. In these latter compounds, the diphosphine heteroatom(s) begins to play a role in the stabilization of the overall molecule through a weak interaction with the metal, thereby generating an expansion of the coordination sphere from sp or tbp into pseudo-octahedral.

By shortening the length of the diphosphine chelate size to five members (including the heteroatom), we find that the stereochemistry of the resulting complexes becomes less easily predictable.

For example, we have recently reported a class of nitrido mixed-chelate complexes of the general formula $M(N)Cl_2(PNP2)$,[7] and related cationic species $[Tc(N)(PNP2)(dtc)]^+$, where PNP2 is a diphosphine incorporating a tertiary amine nitrogen in a five-membered chain and dtc is a monoanionic

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dithiocarbamate,[12] in which the aminodiphosphine exhibits a *cis*-P arrangement and a facial coordination. To gain further insight on the factors determining the preferred molecular stereochemistry of diphosphine-containing complexes, we have explored the reactivity of other potentially tridentate PXP ligands (see Figure 1), having different heteroatoms in the methylene chain.

If we exclude the possibility for a phosphine P to accommodate trans to the terminal nitrido group (such a configuration has never been X-ray authenticated in the literature so far), three different isomeric forms *fac*,*cis*, *mer*,*cis*, and *mer*,*trans* are accessible (see Scheme 1). All of these three forms were isolated and characterized. The stereochemistry of these compounds depends primarily on the nature of the diphosphine heteroatom X. According to the pictorial description reported in Scheme 2 for technetium complexes, except for PNP1 which incorporates a secondary amine group in the backbone, all of the diphosphines yield the *fac*,*cis*-isomer as the kinetic product. The nucleophilicity of the PXP heteroatom appears to be the determining factor for the selected type of coordination. In fact, despite their encumbering environments, strong nucleophilic donors such as the thioetheric S in PSP, or the tertiary amine nitrogen in PNP2 and PNP24, are found to accommodate trans to the Tc≡N group, whereas less encumbering (but less nucleophilic) secondary amine nitrogen in PNP1 is forced to the equatorial coordination by the presence of competitive nucleophiles (halides).

fac,*cis*-Tc(N)Cl$_2$(PN(R)P) complexes are stable both in the solid state and in the solution state, whereas *fac*,*cis*-Tc(N)Cl$_2$(PSP) gives rise to an equilibrium with the *mer*,*trans*-Tc(N)Cl$_2$(PSP) form, and *fac*,*cis*-Tc(N)Cl$_2$(POP) is quantitatively converted into the *mer*,*trans*-Tc(N)Cl$_2$(POP) complex. The facial-meridional isomerization in POP-complexes is consistent with the established trend typical of phosphine-containing compounds to achieve a reciprocal *trans*-P configuration. Such isomerization is consistently slowed in the isostructural PSP-complex, likely for the increased bulkiness of the thioetheric sulfur. This facial-meridional interconversion does not operate in the case of PN(R)P-complexes, for which DFT calculations showed that facial coordination grants the minimization of the steric constraints of the amino-diphosphine bridging chain and increases the efficiency of the N → metal interaction.[7] However, by shortening the length of the substituent at the PNP-amine function to a methyl group, only in the case of rhenium, another facial-meridional isomerization takes place giving rise to a mixture of *mer*,*cis*-Re(N)Cl$_2$(PNP24) in equilibrium with *fac*,*cis*-Re(N)Cl$_2$(PNP24) (Scheme 4).

It has to be highlighted that all of the *fac*,*cis*-Tc(N)Cl$_2$(PXP) complexes readily undergo exchange reactions, by substitution of electron depleted and geometrically prone halide donors, with bidentate nucleophiles (H_2L^n), giving mixed complexes of the type *fac*-Tc(N)(L^n)(PXP) (Scheme 3). The meridional isomers, either *mer*,*cis*- and/or *mer*,*trans*-complexes, which are in equilibrium with their corresponding kinetic *fac*,*cis*-forms, undergo substitution reactions as well, but at a reduced rate. On the contrary, meridional species which do not experience equilibria with facial isomers, as for *mer*,*cis*-Tc(N)Cl$_2$(PNP1), do not undergo exchange reactions, indicating that halides adopting a *cis*-configuration spanning an equatorial and an axial position are much less labile than those adopting a whole equatorial *cis*-arrangement in facial-type complexes.

Hence, this study confirms that *fac*,*cis*-M(N)Cl$_2$(PXP) compounds adopt the best arrangement for subsequent halide substitution and, among the potentially tridentate PXP diphosphines including a five-membered chain, PN(R)P aminodiphosphine ligands represent the ideal choice.

Comparison of the reactivity exhibited by Tc and Re precursors with these PXP diphosphines (Scheme 2 vs Scheme 4) shows evidence of expected similarities, but also important differences. For example, PSP and PNP1 did not show reactivity toward Re nor under the conditions utilized for the Tc congener, neither under drastic conditions (prolonged reaction times, higher temperature). Similar, but not identical reactivity, is instead exhibited by POP and PN(R)P ligands through the formation of the *fac*,*cis*-M(N)Cl$_2$(PXP) key intermediate. As a general comment, in addition to the well-known different radiolysis problems induced by low-level γ-emitter ^{99m}Tc and high-level γ/β-emitters $^{186/188}$Re, dissimilar Tc and Re reactivities have to be taken into account when designing new ^{99m}Tc-radiopharmaceuticals based on studies performed at macroscopic scale utilizing only rhenium complexes or, conversely, when designing new $^{186/188}$Re-radiopharmaceuticals based on the huge literature of existing ^{99m}Tc-compounds.

Conclusions

fac,*cis*-, *mer*,*cis*-, and *mer*,*trans*-M(N)Cl$_2$(PXP)-type complexes were obtained by reactions of PXP diphosphines having a five-membered framework with labile nitrido-containing Tc and Re precursors. The stereochemistry depended primarily on the nature of the diphosphine heteroatom X (O, S, NH, NR; R = CH_3, $CH_2CH_2OCH_3$). PNP1, incorporating a secondary amine group (X = NH), yielded only the *mer*,*cis*-isomer, whereas other diphosphines (POP, PSP, and PN(R)P) produced the kinetic *fac*,*cis*-isomers. Equilibria of the facial with meridional species, either *mer*,*cis*- or *mer*,*trans*-, were observed, and the rate of isomerization depended again on X. *fac*,*cis*-M(N)Cl$_2$(PXP) compounds adopted the best configuration for subsequent halide substitution, and, among the tridentate PXP diphosphines utilized in this study, PN(R)P-like ligands represented the choice of election for the synthesis of [M(N)(BID)(PXP)]$^{+,0}$ mixed-chelate nitrido complexes (BID = monoanionic or dianionic bidentate ligand).

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Supporting Information Available: X-ray crystallographic data for **1**·CH_2Cl_2, **4f**·MeCN, and **8m**·$^1/_2$MeOH in cif format. This material is available free of charge via the Internet at http://pubs.acs.org.

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