A Computational and Conceptual Density Functional Theory Study of the Properties of Re and Tc Tricarbonyl Complexes

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A computational and conceptual density functional study has been performed on metal tricarbonyl complexes (MTC) of both Re(I) and Tc(I). The fully optimized complexes of *fac*-$[Tc(OH_2)(CO_3)]^+$ and *mer*-$[Tc(OH_2)(CO_3)]^+$ show geometries that compare favorably with the X-ray data. These structures were used as a starting point to investigate the relative stability of MTC complexes with various ligands containing combinations of N, O, and S as chelating atoms and to evaluate the stabilizing/destabilizing influence of these ligands. Both for Tc and for Re complexes the nitrogen content turns out to be decisive in the stability of the metaltricarbonyl complexes, the finer details being determined by the hardness sequence N > O > S. As the core of the complexes, $[(M(CO)_3{}^+]$, is hard, the main ordering parameter is changed as compared to our previous studies on Tc(V) [3+1] complexes where the number of sulfur atoms was decisive in accordance with the much softer character of the MOCl core. All results are successfully interpreted in terms of the hard and soft acids and bases principle (HSAB) at the local level.

I. Introduction

Radiopharmaceutical chemicals are routinely used in nuclear medicine, both for diagnostic and for treatment purposes.[1−3] Nowadays, ^{99m}Tc is the most commonly employed radionuclide,[4] because of its nuclear properties, availability, and low cost. ^{99m}Tc that can be daily obtained as ^{99}Tc pertechnetate by elution from a ^{99m}Mo generator has "the" radionuclidic properties promoting it as an ideal for SPECT (single photon computed tomography) diagnosis in nuclear medicine.[4] ^{99m}Tc with a half-life of about 6 h emits a single photon with an energy of 141 keV, which makes it suitable for imaging with crystal-based topographic devices (SPECT) and also makes it "patient friendly" because burden doses are low. Recently, two radionuclides of rhenium, ^{186}Re and ^{188}Re, have been suggested as isotopes with valuables applications in radiotherapy. The latter of these isotopes, ^{188}Re, can be obtained from ^{188}W/^{188}Re generators commercially available since 1989.[5−7]

Chemically, the synthetic route includes the reduction of $[ReO_4]^-$ eluted from the generator, using Sn(II) in a way analogous to that used for ^{99m}Tc. Among a broad variety of species differing in the oxidation state of the Tc and Re atoms and the composition of the ligands used, Tc(I) carbonyl complexes represent a new promising route to low valent, nonpolar, and inert Re and Tc compounds.[8−10] Intensive investigation into the Re and Tc carbonyl chemistry led to a one-pot synthesis under normal pressure from TcO_4^- of the organometallic Tc(I) aqua ion $[Tc(CO)_3(H_2O)_3]^+$ as a precursor for complexes containing the small $[Tc(CO)_3]^+$ moiety.

The main characteristics of these carbonyl complexes are a high substitution stability of the three CO ligands and a corresponding lability of the coordinated water molecules, yielding, via easy exchange of a variety of mono-, bi-, and tridentate ligands, complexes of very high kinetic stability. The different mononuclear tricarbonyl complexes are of extraordinary inertness, which is the basis for potential applications in biology and nuclear medicine. A variety of complexes have been synthesized by Alberto et al.:[11] $[MX_3(CO)_3]^{2-}$ (M = Re, Tc) from $[MO_4]^-$ in organic solvents (X = Cl, Br), and $[MX_3(CO)_3]^+$ from $[MO_4]^-$ in water ($X = H_2O$). Also, the imidazole, histamine, and histidine complexes have been synthesized.

Bernard et al.[12] carried out the aqueous synthesis of derivatized cyclopentadienyl complexes of technetium and rhenium. They have demonstrated that the cyclopentadienyl ligand can be coordinated to $[^{99m}Tc(H_2O)_3(CO)_3]^+$ in water by introducing the electron-withdrawing acetyl−Cp group. This study opens a synthetic approach to labeling biomolecules with half-sandwich complexes of particular interest for radiopharmaceutical applications.

Until now mostly proteins, like monoclonal antibodies, and peptides were labeled with $^{99m}Tc(CO)_3$. Some amino acid transporter systems allow the influx of neutral lipophilic and rather voluminous synthetic amino acids. This explains the interest for ^{99m}Tc labeled amino acids for which the ^{99m}Tc tricarbonyl moiety could offer a promising approach.[13]

This leads to the consideration of model structures of the type shown in Figure 1. It is seen that the amino acid tail is connected to the metaltricarbonyl part (MTC) via a spacer (Sp). In the MTC part, the metal, besides three carbonyl groups, has three ligands with complexing atoms of the type S, O, and N in analogy with our previous work on the stability of mixed [3+1] Tc and Re complexes.[14]

This type of structure fits a linear "tube" design to avoid steric hindrance of the amino acid transport protein interaction. It has indeed been shown in experimental affinity data that two structures with the same surface accessible area,[15] but different tube character, exhibit strongly different affinities, the larger value being associated with the larger "tube" character. The

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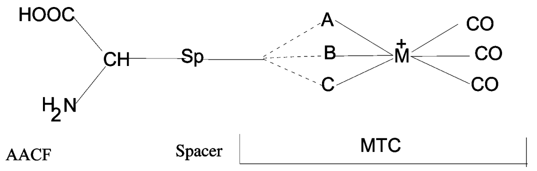


Figure 1. Schematized structures of amino acid tricarbonyl complexes for Tc and Re.

resulting complexes should moreover be "neutral" to be transported by the appropriate transporter complex (LAT1 system), which necessitates the positive charge of the metal to be highly delocalized over the entire MTC part. This calls for an investigation of the charge distribution and stability pattern of these systems.

Ab initio computational techniques[16] are presently increasingly important for the interpretation and guidance of experimental work. Recent developments in this area include the field of density functional theory,[17] which meets with the requirements of being accurate, easy to use, and fast enough to allow the study of relatively large molecules, as the ones of interest in the present study. Hitherto DFT was used in the relatively small number of nonempirical theoretical studies on the chemistry of Tc and Re.[18] Moreover, conceptual density functional theory[19] (for reviews, see ref 20) provides the chemist with a variety of concepts describing reactivity such as electronegativity, hardness, softness, and Fukui functions, which have been successfully correlated with molecular properties and reactivity.

Therefore, we have chosen this tool for performing a quantum chemical study of the properties of Re and Tc tricarbonyl complexes of the type shown in Figure 1 as a sequel to previous work on the relative stability of mixed [3+1] Tc and Re complexes.[14] The properties of the MTC (metaltricarbonyl) part, which will be investigated, are the geometry and electronic charge distribution and are to the best of our knowledge the first studies of this type, with earlier work on $Re(CO)_3$ complexes concentrating on the characteristics of metal to ligand charge-transfer excited states of $(ppRe(CO)_3(L))^{n+}$ systems with pp a bidentate polypyridyl ligand and L an ancillary ligand.[18g]

The organization of this paper is as follows. In the Computational Methods section, we present the choice of an appropriate model system and briefly describe the density functional calculations. In the Results and Discussion section, an extended test is reported of the performance of the method to give a fair description of these complexes by fully optimizing the two organometallic complexes (*fac*-$[M(OH_2)_3(CO)_3]^+$ and *mer*-$[M(OH_2)_3(CO)_3]^+$) with (M = Re, Tc) and comparing the theoretical bond lengths and angles with experimental literature values. A study on the stability and the geometry of the MTC complexes will be done in the case of both Re and Tc with varying ligands with comparison to other theoretical studies. These results will be interpreted in terms of the HSAB principle[20d,21] at local level using hardness values of ligand. To study the relative stability of Re versus Tc complexes, the energetics of the transmetalation reaction $(CO)_3\{Re\}L + Tc \rightarrow (CO)_3TcL + \{Re\}$ is studied for various ligands. Finally, we will investigate the role of the solvent (water) on the stability of the metal tricarbonyl complexes using the polarized continuum model (PCM).[22]

II. Computational Methods

A model system for the one depicted in Figure 1 is given in Figure 2, where the spacer + amino acid part is replaced by a CH_3 group, as the structural and electronic influence of the amino acid tail on the MTC part can be expected to be small, leading to a system showing computational advantages.

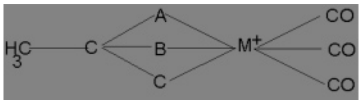


Figure 2. Geometry of the MTC structure with A, B, and C = OH, SH, and NH_2 and M = Re or Tc.

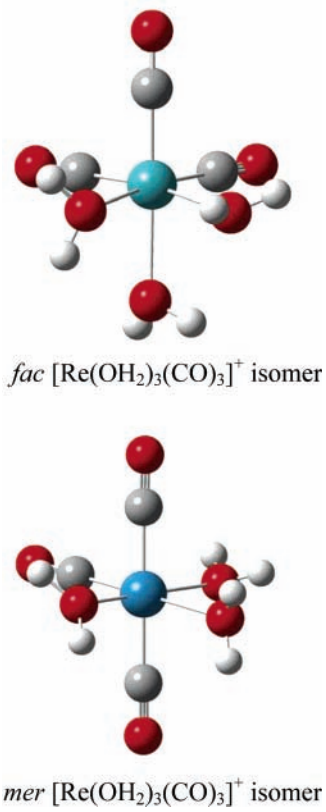


Figure 3. Schematized structure of the *fac*- and *mer*-$[Re(OH_2)_3(CO)_3]^+$ isomers.

The DFT results were obtained using Becke's 1988 exchange functional,[23] combined with the Lee−Yang−Parr correlation functional in the hybrid B3LYP functional.[24] The 6-31++G**[25] basis set has been chosen for the C, H, O, S, and N atoms; for Re and Tc, we have used the LANL2DZ basis,[26] these two options being known to be compatible. To study the stability of the complexes of Re and Tc, all complexes ($[Re(CO)_3L]^+$ and $[Tc(CO)_3L]^+$) were optimized in their singlet state. Atomic charges were calculated with the NPA method[27] in the gas phase and in aqueous solution using the PCM model with water as solvent. All calculations were performed with the Gaussian 03 suite of programs.[28]

III. Results and Discussion

III.1. Geometries. The quality of the computational level was assessed by optimizing the *fac* and *mer* complexes for Re represented in Figure 3 and comparing our calculated geometry with the experimental X-ray results on a similar structure (H_2O + 2,2-bipyridyl).[29] Table 1 gives the calculated B3LYP/LANL2DZ bond lengths and bond angles for a selected number of cases for both the Tc and the Re complexes. From this table, it can be seen that the calculated values show fair agreement with the X-ray results.

The comparison between the B3LYP/LaNL2DZ energies for the *fac* and *mer* isomers of $[Tc(OH_2)_3(CO)_3]^+$ and $[Re(OH_2)_3$-

TABLE 1: Selected Geometrical Parameters (Bond Distances (Å), Bond Angles (deg)) in *fac*-[M(OH$_2$)$_3$(CO)$_3$]$^+$ M = (Re, Tc): B3LYP/LANL2DZ Results versus X-ray Data

bond	B3LYP/ Lan2DZ	X-ray	angle	B3LYP/ Lan2DZ	X-ray
Tc−O	2.286	2.21	O−Tc−O	77.4	84.2
Tc−O	2.284	2.21	O−Tc−O	77.7	83.6
Tc−O	2.284	2.21	O−Tc−O	77.5	83.9
Tc−C	1.925	1.92	Tc−C−O	178.8	178.1
Re−O	2.274	2.19	O−Re−O	77.2	82.5
Re−O	2.274	2.19	O−Re−O	76.9	83.4
Re−O	2.274	2.19	O−Re−O	76.8	83.3
Re−C	1.917	1.91	Re−C−O	178.5	176.4

TABLE 2: Selected Geometrical Parameters (Bond Distances (Å), Bond Angles (deg)) in TcOOO Tricarbonyl Complexes: B3LYP/LANL2DZ Results versus X-ray Data

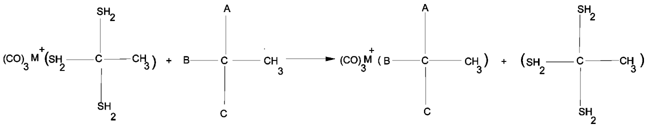
bond	B3LYP/ Lan2DZ	X-ray	angle	B3LYP/ Lan2DZ	X-ray
Tc−O	2.25	2.21	O−Tc−O	77.4	84.2
Tc−O	2.26	2.21	O−Tc−O	77.8	83.6
Tc−O	2.25	2.21	O−Tc−O	77.8	83.9
Tc−C	1.92	1.92	C−Tc−O	178.2	177.8
Re−O	2.24	2.16	O−Re−O	77.4	82.5
Re−O	2.24	2.16	O−Re−O	77.8	83.4
Re−O	2.24	2.16	O−Re−O	77.8	83.3
Re−C	1.91	1.91	Re−C−O	178.2	177.8

(CO)$_3$]$^+$ shows that in both cases the *fac* isomer is more stable than the *mer* isomer (by 21.4 kcal/mol (Tc) and 24.8 kcal/mol (Re) in accordance with the literature),[30] where MP2 calculations yield an energy difference of 27 kcal/mol, for the [Tc(OH$_2$)$_3$(CO)$_3$]$^+$ case.

In a second step, we studied the geometry of the metaltricarbonyl complexes (MTC) given in Figure 3 with varying ligands L. The geometry in the case of A = NH$_2$, B = NH$_2$, C = NH$_2$, and M = Re or Tc is given in the Supporting Information.

Table 2 gives the B3LYP/LAN2DZ lengths for TcOOO metal tricarbonyl complexes (see Figure 3), showing reasonable bond distances as compared to the X-ray results.[31] The Tc−S bond turns out to be larger than the Re−S one, probably due to the lanthanide contraction effect[32] in analogy with the higher softness for Tc than for Re.[14] On the other hand, the Re−S and Tc−S bond lengths in the present study are larger than those found in the case of the [3+1] complexes in our previous work, probably due to a different type of interaction between the metal and the ligand. The trans angles at Re and Tc show a slight deviation from the case of an ideal octahedral arrangement probably due to the cage form of the ligand.

III.2. Stability. The comparison of the stability sequence of a series of Re and Tc complexes will be performed on the basis of the reaction energy (ΔE) of the substitution reaction shown below with A, B, and C = OH, SH, and NH$_2$ and M = Tc, Re:



where we will use a shorthand notation for (SH$_2$)$_3$–C−CH$_3$ as ligand L$_1$ and ...(ABC)−C−CH$_3$ as ligand L$_2$.

The substitution reaction energy is then given by

$$\Delta E = [E((\mathrm{CO})_3\mathrm{M}^+\mathrm{L}_1) + E(\mathrm{L}_2)] - [E((\mathrm{CO})_3\mathrm{M}^+\mathrm{L}_2) + E(\mathrm{L}_1)]$$

and can be used as an indicator of relative stability of the complexes.

TABLE 3: Calculated Substitution Energy ΔE for MTC Complexes with Varying Ligand (Values in kcal/mol) in the Gas Phase and in Solvent

Re complexes	ΔE gas phase	ΔE solvent	Tc complexes	ΔE gas phase	ΔE solvent
ReSSS	0.0	0.0	TcSSS	0.0	0.0
ReNNN	−18.3	−32.6	TcNNN	−16.3	−28.9
ReNNO	−6.8	−20.4	TcNNO	−5.7	−18.0
ReNNS	−12.9	−23.6	TcNNS	−11.4	−21.8
ReNOS	1.3	−7.6	TcNOS	1.1	−6.6
ReOON	5.4	−7.7	TcOON	4.8	−6.5
ReOOO	16.1	3.2	TcOOO	14.5	2.8
ReOOS	15.2	3.9	TcOOS	13.8	3.7
ReSSN	−4.7	−10.6	TcSSN	−4.2	−9.5
ReSSO	10.1	3.0	TcSSO	9.2	2.8

For computational simplicity, ΔE values are used in our study and not ΔG. It should, however, be mentioned that in a very recent study on ligand exchange reactions of the system [Tc(CO)$_i$(H$_2$O)$_{6-i}$]$^+$ ($i = 0-6$), in which the total number of particles is unchanged before and after reaction as is the case in our study, the approximation $\Delta G \approx \Delta E$ has been put forward as the entropies of reactants and products are approximately the same.[30]

The results are given in Table 3. Note that (SH$_2$)$_3$−C−CH$_3$ is taken as reference for both the Re and the Tc complexes.

The sequence of stability for the two metal complexes is the same. This agrees with the highly similar properties of Tc and Re and their place in the periodic table. From Table 3, we can deduce the following stability sequences: 3N > 2N > 1N > 0N and N > S > O, indicating increasing stability for complexes with increasing number of nitrogen atoms, the complexes (CO)$_3$−M−(NH$_2$)$_3$−C−CH$_3$ (M = Tc or Re) being the more stable ones. Nitrogen-containing ligands thus play a crucial role in the stability of the metal tricarbonyl complexes. Note that (CO)$_3$−M−(SH)$_3$−C−CH$_3$ is more stable than (CO)$_3$−M−(OH)$_3$−C−CH$_3$, in accordance with the results found in our previous publication[14] and those found by Liu in studying the Tc complexes using SAS values.[33−35] Globally, if we compare our results with the [3+1] complexes of the Re(V) and Tc(V) study, the sequence of stability is inverted between N and S. An explanation will be put forward later in this work.

In Figure 4a and b, we plotted the ligand substitution reaction energy versus the number of nitrogen atoms showing the "fine structure" of the stabilization energy for different ligands with the same number of nitrogen atoms. In the case of 2 nitrogen atoms, the stability sequence TcNNS > TcNNO gives an indication that the N atom contributes to a larger extent to the stability of the metal tricarbonyl complex and also that the sulfur ligand yields more stabilization than the oxygen one in accordance with the study found by Liu. In the case of the Re atom, the results are similar to the Tc tricarbonyl complexes (ReNNS > ReNNO). In the case of a single nitrogen atom, the stability sequences TcSSN > TcONS> TcOON and ReSSN > ReONS > ReOON indicate that the sulfur ligand more efficiently stabilizes the complex than the oxygen one. These results are confirmed by analyzing the stability sequence for ligands without nitrogen atoms: ReSSS > ReSSO, ReOOS > ReOOO, and TcSSS > TcSSO > TcOOS > TcOOO. Globally, from those two figures the stability sequence for the metal complexing ligand is N > S > O.

These trends can be interpreted within the context of conceptual DFT using the hard and soft acids and bases (HASB) principle,[21] stating that "hard acids prefer to bond to hard bases and soft acids prefer to bond to soft bases." In our previous

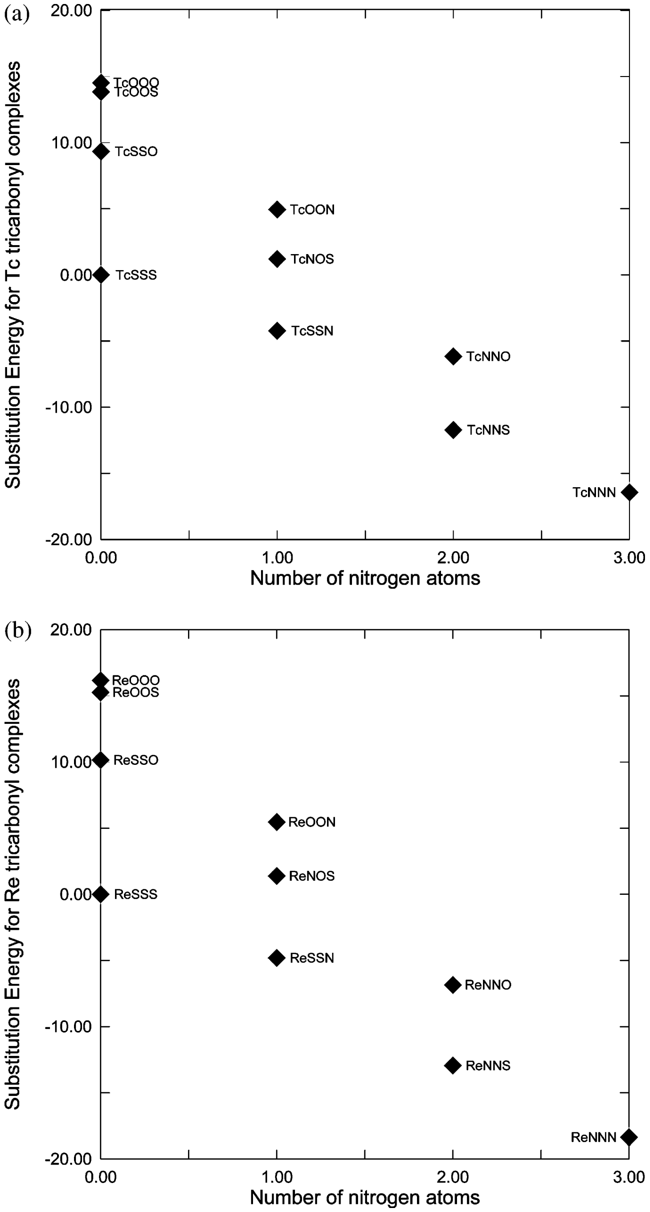


Figure 4. (a) Substitution energy (kcal/mol) for Tc tricarbonyl complexes versus number of nitrogen atoms. (b) Substitution energy (kcal/mol) for Re tricarbonyl complexes versus number of nitrogen atoms.

publication on the [3+1] complexes of the Re(V) and Tc(V), the sequence of stability was S > N > O. This result was explained using the HSAB principle in terms of increasing stability upon increasing ligand softness because, in the oxo technetium complexes considered, the TcOCl core is a soft group as reflected in its preference to bond preferentially to a soft atom like sulfur yielding the following sequence of stability: S > O > N. In the present study, the $[Tc(CO)_3]^+$ nucleus is a hard group, as reflected in its preference for bonding to a hard group, giving the following sequence of stability for the metal tricarbonyl complex: N > S > O.

Note that much of the coordination chemistry of Tc and Re involves medium hard ligands containing nitrogen (e.g., pyridine, imidazole).[36] Tc(I) tricarbonyl complexes have the highest affinity for N, whereas Tc(V) prefers S. The hardness of the $[Tc(CO)_3]^+$ group shows up as follows. Consider the variation of the hardness of $Tc(CO)_i(OH_2)_{6-i}$ versus the number of CO groups (Figure 6). The hardness values can easily be obtained by extending the working equation[37] to

$$\eta = \frac{\epsilon_{\mathrm{LUMO}} - \epsilon_{\mathrm{HOMO}}}{2} \qquad (1)$$

with ϵ_{LUMO} being the energy of the lowest unoccupied molecular orbital and ϵ_{HOMO} being the energy of the highest occupied molecular orbital.

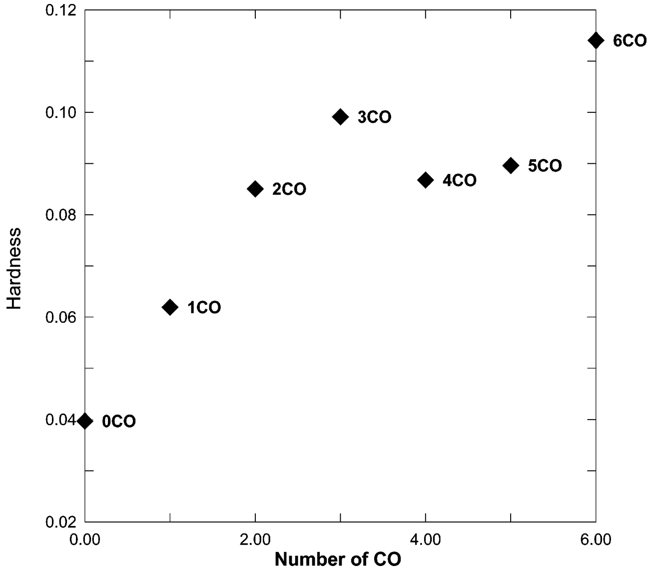


Figure 5. Variation of the hardness (au) of $Tc(CO)_i(OH_2)_{6-i}$ ($i = 0-6$) versus the number of CO ligands.

From Figure 5, we can see clearly that the HOMO−LUMO gap increases, although CO itself is less hard than H_2O (7.9 vs 9.5 eV),[38] indicating that the hardness is enhanced by increasing the number of CO ligands in the complexes. This finding is in agreement with the recognized π-electron-withdrawing properties of the CO ligand.[39] Note that the value of the hardness of Tc^+ (1.48 eV) calculated following the same method used previously is smaller than that of the complex $[Tc(CO)_3(OH_2)_3]$ (2.70 eV) (Figure 5), proving that Tc(I) and Re(I) tricarbonyl complexes are superior in terms of ligand flexibility to the more classical labeling procedure based on Tc(V)=O and Re(V)=O complexes.[40] These findings are in agreement with the theoretical[30] and experimental results[13] in studying the structure, energy, and stability of species formed in the preparation of *fac*-$[^{99m}Tc(CO)_3(H_2O)_3]^+$, indicating that this complex is the dominant species when the pressure of CO is 0.1 MPa as experimentally observed. Following this idea, $[Tc(CO)_3]^+$ is a hard core preferring a hard group with which to interact, giving the following stability sequence: N > O > S. Looking more into detail, our calculated stability sequence seems to be inverted for S and O if we compare it with the stability sequence using the HSAB principle. To refine the picture, we calculated the NPA charges on the N, S, and O atoms in the metal complexes given in Table 4. The analysis of these values shows that the S atom can be expected to be positively charged as compared to the N and O atoms. The use of neutral atom hardness/softness values for the evaluation of the ligand softness should therefore be corrected with η values for the cation in the case of the sulfur atom.

These values can easily be obtained by extending the working equation

$$S = \frac{1}{I_1 - A} \qquad (2)$$

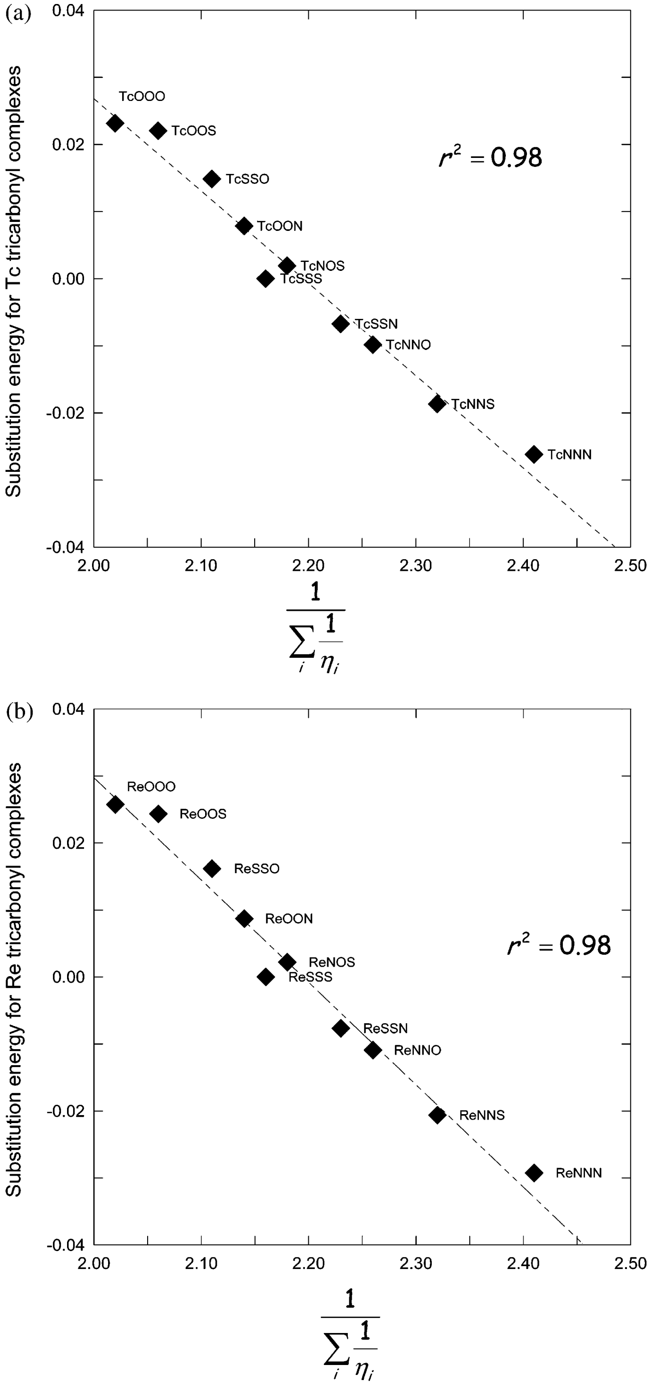


Figure 6. (a) Substitution energy for Tc tricarbonyl complexes versus the hardness (in eV^{-1}) of the ligands. (b) Substitution energy for Re tricarbonyl complexes versus the hardness (in eV^{-1}) of the ligands.

(I_1 being the first ionization energy and A being the electron affinity) from neutral atoms to cations. One then obtains

$$S(\text{cation}) = \frac{1}{I_2 - I_1} \tag{3}$$

where I_2 is the second ionization energy. Using the data from ref 17, one obtains the following hardness sequence for O, N, and S, including both neutral atoms and cations:

$$S^0 << O^0 < S^{+1} < N^0$$

$$\eta = 4.14\ (\text{eV}) \quad 6.08 \quad 6.48 \quad 7.24$$

TABLE 4: NPA Charges (au) on Tc, N, S, and O in MTC Complexes in the Gas Phase

atoms in TcNNN	NPA	atoms in TcSSS	NPA	atoms in TcOOO	NPA
Tc	−0.2458	Tc	−0.6071	Tc	−0.0647
N	−0.8624	S	0.1334	O	−0.7635
N	−0.8626	S	0.1334	O	−0.7634
N	−0.8629	S	0.1352	O	−0.7637

TABLE 5: Calculated Metal Exchange Energy Δ*E* (in kcal/mol) for Varying Ligands

ligands	Δ*E*
SSS	23.9
NNN	25.9
NNO	24.6
NNS	25.2
NOS	23.8
OON	23.4
OOO	22.3
OOS	22.5
SSN	24.6
SSO	23.1

The hardness of S atom is strongly increased and becomes larger than that of the oxygen atom, explaining the (N > S > O) stability sequence of the metal tricarbonyl complexes. A comparable charge effect was observed in the [3+1] complexes, leading to the inversion of the N, O sequence.[14]

To refine the picture on the relationship between complex stability and the structure of the ligand, we plotted in Figure 6 the ligand substitution reaction energy and the hardness of the ligands for Re and Tc metaltricarbonyl complexes, respectively. The hardness of the ligand was approximated via the values of the hardness of the varying part of th group $CH_3-C-(ABC)$ with A, B, and C = OH, SH, and NH_2 calculated on the basis of the sum of the A, B, and C hardnesses taken from ref 17 using the softness additivity principle[41] and using the working equation.

$$\eta = \frac{1}{\sum_{i=1}^{n} \frac{1}{\eta_i}} \tag{4}$$

From Figure 6a and b, it is obvious that the behavior for Re and Tc shows a comparable pattern for the stabilities of their complexes. A very good correlation was obtained between ΔE and the hardness of the ligand, indicating that an increasing hardness of the ligand stabilizes the complexes. From these figures, we obtained the same stability sequence as found previously (N > S > O).

To study the relative stability of Re versus Tc complexes, we have used a simple substitution reaction of type $(CO)_3\{Re\}L + Tc \rightarrow (CO)_3TcL + \{Re\}$, L being the same series of ligands used before. The reaction energy is given as $[E((CO)_3TcL) + E(Re)] - [E((CO)_3ReL) + E(Tc)]$ with $E((CO)_3ML)$ as the energy of the complex. E(Re) and E(Tc) are the energy values of the Re and Tc atoms at their lowest energy for a sextet multiplicity ($E(\text{Re}) = -78.84559$ au and $E(\text{Tc}) = -79.94843$ au).[14]

Table 5 gives the energy of the transmetalation reaction with varying ligands. The positive energies indicate that the reaction is always favored in the reverse sense TcOL + L → ReOL + L and that all ligands prefer Re to Tc. Re complexes are thus more stable than their Tc analogues, in agreement with experimental results[33−35] and our previous study of various [3+1] complexes of both Re(V) and Tc(V).

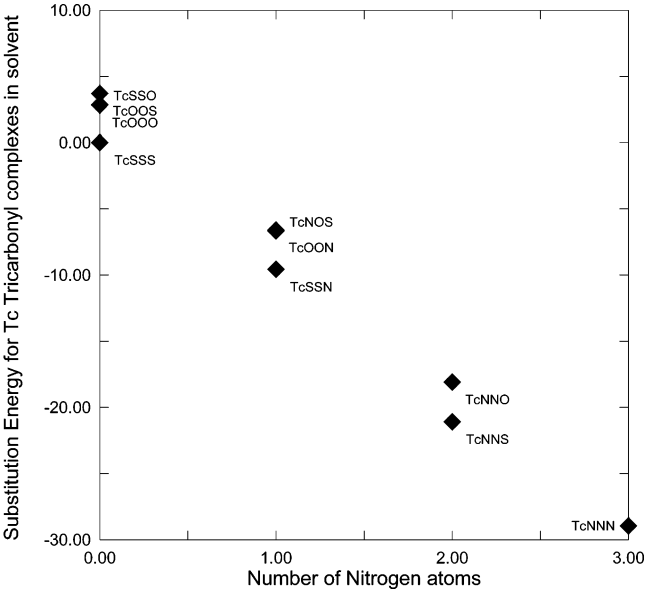


Figure 7. Substitution energy (kcal/mol) for Tc tricarbonyl complexes in solvent versus number of nitrogen atoms.

These trends can again be interpreted within the context of the (HSAB) principle. The "experimental" atomic softness values for Re (0.2583) can be obtained via relationship (2). For Tc, no experimental value is available; a value of 0.3127 (eV^{-1}) was proposed from our previous work by interpolating the softness trend of the neighboring groups of atoms in the periodic table. As can be seen from the ordering of softness of the relevant atoms (values taken from ref 17), Tc (0.3127), Re (0.2583), S (0.2416), O (0.1644), and N (0.1383) eV^{-1}, the two transitions metals are softer than the S, O, and N atoms and S is softer than O and N. As Re is softer than Tc, the smallest local softness difference occurs between Re and the other atoms. From the HSAB principle, it can be inferred that the smaller are the values of this difference, the smaller the transmetalation energy should be and the more the complex will be stable. The HSAB principle can clearly be invoked to explain the sequence of transmetalation reaction energies.

Finally, we investigate the role of the solvent (water) on the stability of the complexes using the polarized continum model (PCM).[22] Figure 7 gives the substitution energy for Tc tricarbonyl complexes calculated in solvent versus the number of nitrogen atoms. From this figure, we can see that the stability sequence in solvent is 3N > 2N > 1N > 0N and N > O ≈ S. This sequence of stability can tentatively be explained as follows: in the solvent, the S atom is less positively charged than in the gas phase (confirmed by the NPA charges on the S atom in the complexes), involving a decrease in its hardness equalizing almost S and O. In general, the N content as determining factor for stability is conserved followed by S except for OOS versus OOO and SON versus OON.

Our study, combined with the one on the Re and Tc(V) [3+1] complexes, nicely shows how the interplay of the softness properties of the core and the ligands determines the opposing stability sequence of the M(I) tricarbonyl complexes and the oxo metal(V) complexes: in the former case, the $M(CO)^{3+}$ core is hard, binding preferentially to ligands via N atoms, and in the latter case the MOCl core of the complex is soft, leading to an outspoken preference for ligand binding via S-atoms, the main ordering parameter for stability thus being the number of S atoms (M(V)) or N atoms (M(I)). Charge reorganization effects, influencing atomic hardness, yield the fine structure sequence S > O > N and N > S > O.

IV. Conclusions

Density functional calculations employing the B3LYP functional and the LANL2DZ basis set have been performed on metal tricarbonyl complexes (MTC) of both Re(I) and Tc(I).

A test of the ability of the methodology to offer a fair description of the geometry of these complexes was performed by fully optimizing the organometallic complexes *fac*-$[Tc(OH_2)(CO_3)]^+$ and *mer*-$[Tc(OH_2)(CO_3)]^+$ 3-thiapentane-1,5-dithiolato) oxotechnetium(V) **2**. It was shown that the results are in fair agreement with X-ray data. The stability of the complexes of a given metal Re or Tc was evaluated using a simple substitution reaction. The calculated reaction energies $\Delta E = [E((CO)_3M-L_1) + E(L_2)] - [E((CO)_3M-L_2) + E(L1)]$ were successfully correlated with the number of nitrogen atoms. The nitrogen content of the ligand thus plays a crucial role in the stability of the metal tricarbonyl complexes. This analysis also shows that for ligands containing three identical sulfur or oxygen atoms, the sequence of stability is SSS > OOO, in agreement with the results found by Liu. The rhenium complexes are found to be more stable than their technetium analogues. All results are successfully interpreted in terms of the hard and soft acids and bases (HSAB) principle, applied at the local level.

Finally, the role of the solvent (water) on the stability of the complexes using the polarized continuum model was determined. The stability sequence in solvent is 3N > 2N > 1N > 0N and N > O ≈ S. In general, the N content as the determining factor for stability is conserved followed by S, except for OOS versus OOO and SON versus OON.

Combined with our study on the Re and Tc(V) [3+1] complexes, our study nicely shows how the interplay of the softness properties of the core and the ligands determines the opposing stability sequence of the M(I) tricarbonyl complexes versus the oxo metal(V) complexes.

All in all, these studies indicate that conceptual DFT, in casu application of the HSAB principle at the local level, offers a parameter-free approach to interpret and systematize experimental and theoretical binding characteristics for metals such as Re and Tc lying deep in the periodic table, high in interest for nuclear medicine.

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Supporting Information Available: Geometries (Cartesian coordinates) of all complexes and ligands. Figure with the geometry of the MTC complex with $A = B = C = NH_2$ and M = Re or Tc. This material is available free of charge via the Internet at http://pubs.acs.org.

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