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Reductive N–N coupling of NO molecules on transition metal complexes leading to N₂O

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Abstract
Nitric oxide reductase (NOR) type reactions (2NO + 2e⁻ + 2H⁺ → N₂O + H₂O) on transition metal complexes not involving NO disproportionation (3NO → N₂O + NO₂) are reviewed. The former has little reported, although the latter is very common reaction. The formation of N₂O indicates that N–N coupling of two NO molecules is an essential step. A few examples of N–N coupling on transition metal complexes have been structurally characterized, including several examples of hyponitrite (O=N-N=O)²⁻ complexes and only one diruthenium complex bearing neutral (O=N-N=O) binding mode. Protonation or heating their complexes led to elimination of N₂O. In the examination of the NOR-type reaction, only a few functional model complexes for the active site of the metalloenzyme have been developed. These complexes also showed NOR activity. Finally, an NO reduction cycle in the diruthenium system is described.

Keywords: Nitrogen monoxide; N–N coupling; Nitric oxide reductase (NOR); Nitrous oxide; Hyponitrite;

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1. Introduction

The activation of relatively inert small molecules such as \( \text{N}_2 \) and \( \text{CO}_2 \) on transition metal complexes has been fascinating chemists [1]. While nitrogen monoxide (NO) is rather reactive compared with \( \text{N}_2 \) and \( \text{CO}_2 \), the controlled reactivity of NO on transition metal complexes has received considerably less attention. Since NO has an unpaired electron, oxidation to \( \text{NO}^+ \) or reduction to \( \text{NO}^- \) to generate electron paired species easily occurs, which complicates mechanistic understanding. Reactions involving NO regulation occur in biological systems [2], such as blood pressure control, neurotransmission, immune systems, etc., although NO has adverse effects on the environment [3]. Other exquisitely controlled reactivity of NO is shown in the metalloenzyme, nitric oxide reductase (NOR), which is involved in biological denitrification (a four-step process that reduces \( \text{NO}_3^- \) to \( \text{N}_2 \)). NOR is a membrane-bound enzyme that catalyzes the \( 2e^- \) reduction of nitric oxide (NO) to nitrous oxide (\( \text{N}_2\text{O} \)) using two protons, i.e., \( 2\text{NO} + 2e^- + 2\text{H}^+ \rightarrow \text{N}_2\text{O} + \text{H}_2\text{O} [1,4] \). In 2010, the crystal structure of NOR at 2.7 Å resolution was finally revealed [5]. The active site of NORs possesses a heme iron/non-heme iron (FeB) dinuclear center (Fig. 1), which is similar to that of the respiratory enzyme cytochrome \( c \) oxidase (CcO) [6], where CuB occupies the distal position instead of FeB in NOR. The mechanism of the NOR reaction remains a matter of debate [7]. However, it clearly involves intriguing N–N bond formation and N–O bond cleavage on transition metal complexes.

(Fig. 1 here)

The binding of NO to metal ions to afford metal-nitrosyl compounds can involve linear M–N–O geometry (NO\(^+\)) or bent M–N–O geometry (NO\(^-\) and NO\(^-\)). The geometry of M–N–O units can be predicted from the coordination number and the Enemark-Feltham electron counting formalism \( \{\text{MNO}\}^n \), where \( n \) stands for the combined number of electrons on the metal d and \( \pi^*_{\text{NO}} \) orbitals (or \( n \) represents the number of d electrons on the metal when the NO is formally considered to be NO\(^+\)) [8]. This methodology has proved to be mostly successful to predict the coordination geometries of common metal-nitrosyl complexes, but several exceptions have been reported [9]. A number of comprehensive reviews and chapters about metal-NO complexes have appeared during the past several decades [10].

This review focuses on the NOR-type reaction (conversion of 2NO to \( \text{N}_2\text{O} \) and \( \text{H}_2\text{O} \) using two electrons and two protons) not involving NO disproportionation (3NO -> \( \text{N}_2\text{O} + \text{NO}_2 \)) [1,4a,10]. Metal complex-mediated NO disproportionation is a very common reaction type. In either case, the N–N bond formation (N–N coupling) of two NO molecules on transition metals is a key step in the mechanism. However, only a few examples of N–N coupling on transition metals have been structurally characterized. In this connection two types of N–N coupling have
been determined, namely hyponitrite (O=N=N-O)$^{2-}$ formation and neutral (O=N-N=O)
formation. There is only a single example of the latter. Initially, we describe these complexes
and their ability to release N$_2$O. In addition, discussion about the NOR-type reaction using
structural and functional models of the active site of NOR is reviewed. Finally, an NO
reduction cycle utilizing the unprecedented N–N coupling (neutral (O=N-N=O) form) complex
is described. Two recent reviews have also been written concerning hyponitrite interactions
with transition-metal complexes and bioinspired inorganic chemistry involving NO reduction,
respectively [11].
2. N–N coupling on transition metal complexes and elimination of N$_2$O

2.1. Hyponitrite (O-N=N-O)$^{2-}$ complexes and elimination of N$_2$O

Treatment of Pt(PPh$_3$)$_4$ with NO led to the reductive dimerization of NO to afford a cis-hyponitrite ligated Pt(II) complex [Pt(ONNO)(PPh$_3$)$_2$] (1a) which was structurally characterized (Scheme 1) [12]. The cis-hyponitrite complexes [Ln$_n$M(ONNO)] (M = Ni, Pt; Ln = PPh$_3$, PPh$_2$Me, dppe, and dppf) were also prepared by the reactions of [Ln$_n$MCl$_2$] with diazeniumdiolate RN$_2$O$_2$$^-$. These complexes adopt a diamagnetic square planar geometry with an O-bonded planar chelating cis-hyponitrite ligand. These complexes were sensitive to acids, heat, light, and oxidation, producing N$_2$O and a transient terminal oxido complex [Ln$_n$M=O] which was trapped by reactions with CO$_2$ or CS$_2$. In the thermolysis of [Ni(ONNO)(dppf)] (1b), the kinetics results indicate that the rate-limiting step is unimolecular involving release of N$_2$O.

(Scheme 1 here)

The reaction of a coordinatively unsaturated dinuclear complex [Ru$_2$(CO)$_4$($\mu$-H)($\mu$-P$_3$Bu$_2$)($\mu$-dppm)] with NO resulted in a trans-hyponitrite complex [Ru$_2$(CO)$_4$($\mu$-H)($\mu$-P$_3$Bu$_2$)($\mu$-dppm)($\mu$-ONNO)] (2) which was formed by reductive coupling of two NO molecules (Scheme 2) [14]. In the trans-(ONNO)$^{2-}$ ligand, one of two NO fragments bonds to the diruthenium core in the “side-on” manner, whereas the second one is not connected to the ruthenium. However, in the solid state the noncoordinating O atom exhibits a weak intramolecular bond to the carbon atom of a neighboring CO group. The $^{31}$P{$^1$H} NMR spectrum of 2 shows three double doublet signals, and the $^1$H NMR spectrum exhibits a multiplet hydride signal at $\delta$ = -12.30 ppm. The IR spectrum of 2 shows three bands for terminal carbonyl ligands and one characteristic band at 1742 cm$^{-1}$. The high nucleophilicity of the non-coordinated O atom was proved by O-protonation and -alkylation using HBF$_4$ and [Me$_3$O]BF$_4$, respectively, where the protonated 3a and methylated 3b complexes were confirmed by X-ray crystal structure analyses [15]. The IR spectra of 3a and 3b show only $\nu$(CO) bands that are characteristic of terminal carbonyls, which differs from 2. In their $^1$H NMR spectra, singlet signals corresponding to the NOH and NOMe groups are observed at $\delta$ = 11.13 and 3.10 ppm, respectively. Deprotonation of 3b afforded a neutral trans-hyponitrite derivative complex [Ru$_2$(CO)$_4$($\mu$-P$_3$Bu$_2$)($\mu$-dppm)($\mu$-ONNOMe)] (4), which was also crystallographically characterized [16]. The $^1$H NMR spectrum of 4 exhibits disappearance of the hydride signal. Although the trans-hyponitrite complex 2 was irradiated with UV in THF at room temperature to revert to the starting coordinatively unsaturated complex, thermolysis of the protonated complex 3a afforded a hydroxido-bridged complex [Ru$_2$(CO)$_4$($\mu$-H)($\mu$-OH)($\mu$-P$_3$Bu$_2$)($\mu$-dppm)]BF$_4$, releasing N$_2$O. The bridging hydroxido group
is confirmed by a ν(OH) absorption band at 3567 cm⁻¹ in the IR spectrum and a resonance signal at δ = -0.09 ppm in the ¹H NMR spectrum.

(Scheme 2 here)

A more complicated reaction between the cobalt carbonyl nitrosyl [Co(CO)₃(NO)] and excess NO gave a nitrito- and hyponitrito-bridged complex \([\{\{\text{Co(NO)}\}_2\}_2(\mu\text{-ONO})_2(\mu\text{-ONNO})]\) in low yields (Scheme 3) [17]. The IR spectrum of 5 shows two strong ν(NO) bands at 1850 and 1796 cm⁻¹, which are assignable to the terminal NO groups. The bridging hyponitrite group, which would be formed by reductive dimerization of NO, has a trans configuration, and its two NO fragments coordinate to the \{Co(NO)₂\}_₂(μ-ONO) unit in the “side-on” manner. The formation of the bridging nitrito ligands could arise from disproportionation of NO into NO₂ and N₂O. Pyrolysis of the hyponitrite complex 5 liberated N₂O along with NO, but not NO₂.

(Scheme 3 here)

On the other hand, the ammine cobalt complex \([\text{Co(NH}_3\text{)}_6]^{2+}\) was allowed to react with NO to afford various complexes, the formation of which is largely temperature dependent. Among them, a hyponitrito-bridged complex \([\text{NH}_3\text{)}_3\text{Co}\{\mu\text{-N(O)NO}\}\text{Co(NH}_3\text{)}_3]^{4+}\) (6) was isolated and structurally characterized (Scheme 4) [18]. The two Co(NH₃)₃ units are bridged asymmetrically through a hyponitrite group, where one cobalt atom is bonded to an oxygen atom and the other to a nitrogen atom. The hyponitrite moiety is planar with a cis configuration. Acid treatments of the hyponitrite complex 6 in the absence of air produced N₂O and the aquapentaammine cobalt(III) complex.

(Scheme 4 here)

A hyponitrito-bridged iron porphyrin complex \([(\text{OEP})\text{Fe}](\mu\text{-ONNO})\) (7) (OEP= octaethylporphyrin) was prepared from the reaction of an oxido-bridged iron porphyrin complex \([(\text{OEP})\text{Fe}](\mu\text{-O})\) with hyponitrous acid (Scheme 5) [19]. The X-ray crystal structure reveals that the ONNO ligand is bound to each Fe via the κ¹-O binding mode and that the ONNO moiety is trans. The EPR spectral data of 7 (g = 5.74 and 2.03) as a CH₂Cl₂/toluene glass (77 K) is similar to that of two high-spin ferric hydroxido porphyrins. Protonation of the hyponitrite complex 7 at 0 °C using HCl resulted in the formation of N₂O and \([(\text{OEP})\text{FeCl}]\). The assumption that the protonation is initiated by H⁺ attack on one of the O atoms of the hyponitrito bridge, followed by N-O bond cleavage to give N₂O, was proposed.

(Scheme 5 here)

The first example of the radical dianion of nitric oxide \((\text{NO})^{2-}\) was discovered in an yttrium complex \{[(Me₃Si)₂N]₂(THF)Y\}_₂(μ-NO)\) (Scheme 6) [20]. This complex was allowed to react with another equivalent of NO to afford a diamagnetic trans-hyponitrite complex \{[(Me₃Si)₂N]Y\}_₄(μ-ONNO)₂(THF)₂\) (8). The formation of the hyponitrite moiety can be
rationalized by the coupling of an NO radical with an (NO)\(^2\) radical: \( \text{NO} + (\text{NO})^2 \rightarrow (\text{ON}=\text{NO})^2\). The (ON=NO)\(^2\) ligands chelate \( Y\{\text{N(SiMe}\_3)\_2\}_2 \) via N and O atoms, leading to a four-membered ring. The remaining O atom coordinates to \( Y\{\text{N(SiMe}\_3)\_2\}_2(\text{THF}) \). The two dimers are bridged by the chelating O atoms, resulting in a tetranuclear complex. The reactivity of this complex has not been reported.

(Scheme 6 here)

2.2. N–N coupling (neutral (O=N-N=O) binding mode) complexes and elimination of \( \text{N}_2\text{O} \)

We found unique N–N coupling on dinuclear ruthenium complexes having Tp (= HB(pyrazol-1-yl)\_3) ligands. These complexes were prepared from the reaction of \( \text{TpRuCl}_2(\text{NO}) \) (\( \text{RuNO} \)\(^6\)) with pyrazoles in the presence of excess \( \text{Et}_3\text{N} \) (Scheme 7) [21]. The N-N coupling complexes (\( \text{TpRu}_2(\mu-\text{Cl})(\mu-\text{Rpz})\{\mu-\text{N(=O)-N(=O)}\} \) (9: \( \{\text{Ru}_2(\text{NO})_2\}^{14}\)) consist of the bridging chlorido, pyrazolo, and N(=O)-N(=O) ligands. As can be seen from the Enemark-Feltham electron counting, 2e\(^-\) reduction occurred during the formation of 9. This reductive formation is probably associated with the presence of the excess \( \text{Et}_3\text{N} \), which is essential to the preparation. The X-ray result of 9\(\text{a} \) shows that N–N distance is 1.861(3) Å (Fig. 2), which is much longer than that in the hyponitrite form, indicating NO dimer (vide infra) [22]. At low temperatures, NO molecules dimerize in the \( \text{cis} \) form with weak N–N bonding interaction (2.18 Å). DFT calculations of 9\(\text{a} \) reproduce the molecular structure (N=N= 1.85325 Å), where the HOMO corresponds to N–N bonding (Fig. 2). Observation of such N–N coupling on transition metal sites not involving the hyponitrite form is unprecedented.

(Scheme 7 and Fig. 2 here)

Interestingly, reaction of the unusual N–N coupling complex 9 with an oxidizing agent (AgBF\(_4\) or \( [\text{Cp}_2\text{Fe}]\text{BF}_4 \)) giving \( \{\text{TpRu(NO)}\}_2(\mu-\text{Cl})(\mu-\text{pz})\}([\text{BF}_4])_2 \) (10: \( \{\text{Ru}_2(\text{NO})_2\}^{12}\), led to N–N bond cleavage (Scheme 8). The IR spectrum of this product shows a characteristic \( \nu(\text{N}=\text{O}) \) band, and the structure was confirmed by the X-ray crystallographic analysis (Fig. 3). Bonding interaction between two NO nitrogen atoms is no longer observable as exemplified by an N···N separation of 3.006(8) Å. Reduction of the dinitrosyl complex 10 with \( \text{Zn} \) led to N–N bond formation, regenerating the N–N coupling complex 9. The reversibility of this N–N bonding was supported by the cyclic voltammogram of the N–N coupling complex, which features a reversible two-electron redox process at 0.389 V (\( E_{1/2} \) vs Ag/AgCl) (Fig. 4). Similar attempts to form an N–N bond between two nitrosyl ligands in a dinuclear iron complex have failed. In this case, warming of the dinitrosyl iron complex led to NO ligand dissociation (Scheme 9) [23].

(Scheme 8, Fig 3, Fig. 4, and Scheme 9 here)

Protonation of the N–N coupling complex 9 triggered elimination of \( \text{N}_2\text{O} \) (Scheme 10). Treatment of 9 with HBF\(_4\) in \( \text{CH}_2\text{Cl}_2 \) gave an oxido-bridged dinuclear complex
(TpRu)$_2$(μ-Cl)(μ-pz)(μ-O) (11) (21% yield) and the oxidized complex 10 (43% yield), along with evolution of N$_2$O which was detected by gas-chromatography (25% yield based on 11).

(Scheme 10 here)

2.3. Bond distances and angles and IR stretching frequencies for N$_2$O$_2$ frameworks of N–N coupling compounds

The N–N and N–O distances and O–N–N angles in the N$_2$O$_2$ framework are summarized in Table 1. In the hyponitrite complexes, the N–N (1.230 ~ 1.267 Å, average 1.255 Å) and N–O (1.307 ~ 1.400 Å, average 1.355 Å) bond distances are very similar to those of simple inorganic salts (trans-Na$_2$(ONNO); N-N = 1.256(2) Å, N-O = 1.3622(11) Å) [24], leading to N–N double bond and N–O single bond, respectively. On the other hand, these distances of complex 9a are obviously different from those of the hyponitrite complexes, but close to NO dimer.

(Table 1 here)

The IR spectra would give useful information of the appearance of the N$_2$O$_2$ moiety. The reported IR wavenumbers associated with the N$_2$O$_2$ stretching vibrations are shown in Table 2, involving those of the related complex K$_6$[Co$_2$(CN)$_{10}$(N$_2$O$_2$)] [25], which is not X-ray crystallographically determined. The IR spectra of 1a and 5 have been reported at the bands (1a, 1285, 1240, 1062 cm$^{-1}$; 5, 1377, 1327, 1098, 828 cm$^{-1}$), but these are not clearly assigned [12b,17]. As can be seen in the IR spectra of two sodium hyponitrite [26], the trans- and cis-N$_2$O$_2^{2-}$ exhibit a single and three IR stretching vibrations, respectively, owing to their symmetry. Although the v(NN) bands of the dinuclear ruthenium complexes (2–4) which have a trans-hyponitrite moiety are observed at 1425 ~ 1484 cm$^{-1}$, other hyponitrite complexes exhibit v(NN) bands in the 1336 ~ 1399 cm$^{-1}$ region. On the other hand, the IR spectra of the neutral N$_2$O$_2$ binding mode complexes 9–9b show a characteristic v(NO) band at ca. 1600 cm$^{-1}$. Assignment of the other v(NO) band is probably hindered by overlapping with the bands associated with pyrazole.

(Table 2 here)
3. NOR-type reaction using functional model complexes

In the examination of the NOR-type reaction, use of the enzymes makes it difficult to elucidate the NO reduction mechanism. Lu et al. have reported excellent engineered metalloproteins to mimic the structure and function of the NOR active site, where three histidines (His) and one or two glutamates (Glu) were introduced in sperm whale myoglobin [27]. Although three His and one Glu residues bind iron, mimicking the FeB site in NOR, introducing the second Glu to the second coordination sphere of the FeB site through a hydrogen bonding network resulted in ~100% increase in NOR activity. Also, the synthetic model complexes that mimic the active site of NOR can help mechanistic understanding. However, only a few synthetic model complexes have been developed.

3.1. Heme Fe/tripyridyl Fe dinuclear system

Karlin et al. have designed model ligands that contain a tetradentate tris(2-pyridylmethyl)amine chelate tethered to a tetraarylporphyrin [28–31]. A heme/non-heme diiron(II) complex $[(\delta L)\text{Fe}^{II}\cdots\text{Fe}^{II}\text{Cl}]^+$ (12) was prepared and allowed to react with NO at low complex concentrations (below 10 μM) to give an oxido bridged complex $[(\delta L)\text{Fe}^{III}\text{O}\text{Fe}^{III}\text{Cl}]^+$ (Scheme 11) [28]. This indicates that each iron contributes one electron and the two NO ligands couple to give N$_2$O (reductive dimerization) leaving the O-atom in the oxido bridged complex. However, N$_2$O was not detected probably because of low concentrations. At high concentrations, both N$_2$O and NO$_2$ were detected. Therefore Karlin et al. have proposed that N$_2$O is formed via reductive dimerization and NO$_2$ is produced by the reaction of the resulting oxido bridged complex $[(\delta L)\text{Fe}^{III}\text{O}\text{Fe}^{III}\text{Cl}]^+$ with NO. With the related complex $[(\delta L)\text{Fe}^{II}\cdots\text{Fe}^{II}\text{Cl}]^+$, reaction with NO gave a bis-nitrosyl adduct $[(\delta L)\text{Fe}^{II}\text{NO}\text{Fe}^{II}\text{NO}\text{Cl}]^+$ (13) [30]. However, complex 13 is very stable and NO-reductive coupling was not observed upon the addition of proton sources or excess base. Instead, the addition of excess base resulted in ligand-promoted NO dissociation to give $[(\delta L)\text{Fe}^{II}\cdots\text{Fe}^{II}\text{Cl}]^+$.

(Scheme 11 here)

3.2. Heme Fe/tripyridyl Cu dinuclear system

Interestingly, the NOR activity (NO reduction to N$_2$O) has been found in a heme/copper dinuclear reaction system. This resembles heme-copper oxidases, including cytochrome $c$ oxidases (CcO), that are evolutionarily related to NOR. A dinitrosyl complex $[(\delta L)\text{Fe(NO)}_2]$ (14) was synthesized at low temperatures and allowed to react with a copper source, [Cu'(MeCN)$_4$]B(C$_6$F$_5$)$_4$, and 2 equiv acid (H(OEt)$_2$)[B(C$_6$F$_5$)$_4$]) to afford N$_2$O in very good yield and $[(\delta L)\text{Fe}^{III}\cdots\text{Cu}^{II}(D)]^{3+}$ (D = MeCN or H$_2$O) (Scheme 12) [31]. In control experiments,
the dinitrosyl complex 14 was protonated at -80 °C and then warmed to room temperature to afford a mono nitrosyl complex (\(^6L\)Fe(NO), releasing NO. On the other hand, absence of protons led to N\(_2\)O and a heme-nitrosyl\(\cdots\)Cu-nitrite complex \([\((^6L)\text{Fe(NO)}\cdots\text{Cu}^{II}(\text{NO}_2)\)]^+\), indicating a copper complex mediated disproportionation reaction. Thus, a stoichiometric functional model system for heme/nonheme diiron NOR has been demonstrated, i.e., \([\((^6L)\text{Fe}^{II}\cdots\text{Cu}^{I}\)]^+ + 2\text{NO} + 2\text{H}^+ \rightarrow [\((^6L)\text{Fe}^{III}\cdots\text{Cu}^{II}\)]^+ + \text{N}_2\text{O} + \text{H}_2\text{O}\).

Moreover, a 1:1 mixture of a heme (F\(_8\)Fe (F\(_8\) = tetrakis(2,6-difluorophenyl)porphyrinate(2-)) and a copper complex [(tmpa)Cu\(^I\)(MeCN)]\(^+\) (tmpa = tris(2-pyridylmethyl)amine) components has also facilitated NO reduction to N\(_2\)O. A dinitrosyl complex (F\(_8\)Fe(NO)\(_2\) (15) was allowed to react with [(tmpa)Cu\(^I\)(MeCN)]\(^+\) and 2 equiv of acid (H(OEt\(_2\))[B(C\(_6\)F\(_5\))\(_4\)]) to afford \([\((F_8)\text{Fe}^{III}\)]^+\), [(tmpa)Cu\(^II\)(solvent)]\(^2+\), and N\(_2\)O (Scheme 13) [32], corresponding to the stoichiometric NO reductive coupling reaction: 2\text{NO} + \text{Fe}^{II} + \text{Cu}^{I} + 2\text{H}^+ \rightarrow \text{N}_2\text{O} + \text{Fe}^{III} + \text{Cu}^{II} + \text{H}_2\text{O}\). Control experiments showed that both iron and copper centers are required for the observed NOR-type chemistry and that, if acid is not present, half of the NO is trapped as a (F\(_8\)Fe(NO)) complex, while the remaining NO undergoes copper complex promoted disproportionation chemistry. Heme–Fe\(^{II}\), Cu\(^I\), and acid are all required to trigger the NOR-type reaction. The protonated hyponitrite (HONNO\(^-\)) dinuclear intermediate, where N atoms bind to both the metal ions, has been suggested. This protonated hyponitrite intermediate (\(\text{trans}\)-mechanism) has been also supported by biophysical studies and DFT calculations [7].

3.3. Heme Fe/trisimidazole Fe dinuclear system

Collman et al. have reported biomimetic ligands featuring a porphyrin with three imidazole pickets at the distal site and an imidazole ligand at the proximal site. Both the distal and proximal ligands are covalently attached to the porphyrin [33,34]. Collman et al. prepared the synthetic model complex LFe\(^{II}\)/Fe\(^{II}\) (16), which was allowed to react with two equivalents of NO to give one equivalent of N\(_2\)O and a bis-ferric product LFe\(^{III}\)-NO/Fe\(^{III}\)-OH (Scheme 14) [34]. During the NO reduction, the proximal imidazole remains coordinated to the heme iron, which enhances the radical character of the heme nitrosyl. This should be advantageous for the N–N coupling step. On the other hand, the reaction of the mixed-valence form LFe\(^{III}/Fe\(^{II}\) with NO gave a mixture of LFe\(^{III}\)-NO/Fe\(^{II}\)-NO and LFe\(^{II}\)-NO/Fe\(^{III}\) without NO reduction. The spectroscopic data of the NO reduction reaction indicates that the first NO binds to Fe\(_B\) forming a high-spin Fe\(_B\)-NO species (A), followed by another NO binding to heme Fe\(^{II}\). This results in the formation of an LFe\(^{II}\)-NO/Fe–NO species (B) which then forms N\(_2\)O and the bis-ferric
product $\text{LFe}^\text{III}-\text{NO/Fe}^\text{III}-\text{OH}$. Interestingly, these data also indicate that in the bis-nitrosyl intermediate B the two nitrosyls are close enough to either spin-dipole couple or directly interact.

(Scheme 14 here)
4. NO reduction cycle (Ru dinuclear system supported by Tp ligands)

Our ruthenium system has achieved an NO reduction cycle. The oxido-bridged complex 11, which was produced by proton-induced elimination of N₂O in 9, was allowed to react with 1 equiv of HBF₄ in diethyl ether to give a hydroxo-bridged dinuclear ruthenium complex \([(TpRu)_2(\mu-Cl)(\mu-OH)(\mu-pz)]BF_4 \) (17) (Scheme 15) [21b]. The \(^1\text{H}\) NMR spectrum of 17 indicates paramagnetism, although the NMR spectrum of 11 shows diamagnetism probably owing to strong antiferromagnetic spin exchange coupling via a superexchange mechanism [35]. Protonation of the oxido bridge in 11 weakens the orbital overlap between the Ru \(\sigma\) and oxygen \(\pi\) orbitals, resulting decrease of the antiferromagnetic coupling. Finally, the structure of 17 was determined by single-crystal X-ray diffraction. Protonation on the bridged oxido ligand was confirmed by the Ru-O distance (2.0038(19) Å), which is longer than that of 4-bromopyrazolato- and oxido-bridged derivative of 11 (1.898(4), 1.904(3) Å) [21a]. Additional protonation of 17 should give an aqua-bridged dinuclear ruthenium \([(TpRu)_2(\mu-OH_2)(\mu-Cl)(\mu-pz)](BF_4)_2 \) (18). Thus in the \(^1\text{H}\) NMR spectrum, when HBF₄ was added to an acetone-d₆ solution of 17, one set of paramagnetic signals appeared, which can be assigned to 18. Isolation of 18 failed, probably owing to easy deprotonation. However, its formation in the reaction mixture was detected by FAB-MS spectroscopy. Thus, after treatment of 17 with HBF₄ for 15h, the reaction mixture was exposed to NO to give the dinitrosyl complex 10 in 53% yield. Reduction of the dinitrosyl complex 10 induced N–N coupling of the two NO ligands, affording the complex 9 (vide supra). These successes led to completion of an NO reduction cycle on the dinuclear ruthenium complex (Scheme 16).

(Scheme 15 and Scheme 16 here)
5. Summary

The NOR-type reactions \(2\text{NO} + 2e^- + 2\text{H}^+ \rightarrow \text{N}_2\text{O} + \text{H}_2\text{O}\) are reviewed. In connection with this, several structurally characterized hyponitrite \((\text{O-N=O})^2-\) complexes and one diruthenium complex bearing an unusual neutral \((\text{O=N-N=O})\) ligand are reported. All of these complexes, except for the yttrium complex 8 where its reactivity is not reported, released \(\text{N}_2\text{O}\) by protonation and heat. Also, a few functional model complexes for the active site of the metalloenzyme (nitric oxide reductase) showed NOR activity. Finally, the NO reduction cycle using the unprecedented N–N coupling complex 9 is presented.

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Scheme 1. Syntheses of group 10 hyponitrite complexes 1 and elimination of N₂O.
Scheme 2. Synthesis of a *trans*-hyponitrite diruthenium complex 2 and elimination of N₂O.
**Scheme 3.** Synthesis of a hyponitrito-bridged cobalt complex 5 and elimination of N$_2$O.

**Scheme 4.** Syntheses of asymmetrical hyponitrito-bridged cobalt complexes 6 and elimination of N$_2$O.
**Scheme 5.** Synthesis of a hyponitrito-bridged iron porphyrin complex 7 and elimination of N₂O.

**Scheme 6.** Synthesis of a *trans*-hyponitrite yttrium complex 8.

Scheme 9. Attempts to form an N–N bond of two NO ligands on a dinuclear iron complex.

Scheme 10. Elimination of N₂O that is induced by protonation of 9.
Scheme 11. NOR activity using a heme Fe/tripyridyl Fe dinuclear system.
Scheme 12. NOR activity using a heme Fe/tripyridyl Cu dinuclear system.
Scheme 13. NOR activity using a 1:1 mixture of a heme Fe and a tripyridyl Cu complex.
Scheme 14. NOR activity using a heme Fe/trisimidazole Fe dinuclear system.
Scheme 15. Double protonation of 11 and subsequent treatment with NO, reforming 10.

Fig. 1. The active site of nitric oxide reductase (NOR).

Fig. 2. ORTEP drawing of the molecular structure of 9a (left) and gaussview depiction of HOMO for the calculated complex 9a (right).
Fig. 3. ORTEP drawing of the molecular structure of 10. BF$_4$ counterions are omitted for clarity.

Fig. 4. Cyclic voltammogram of 9 in CH$_3$CN solution.