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<td>Authors(s)</td>
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<tr>
<td>Publication date</td>
<td>2011-06-16</td>
</tr>
<tr>
<td>Publication information</td>
<td>Chemical Communications, 2011 (47): 8058-8060</td>
</tr>
<tr>
<td>Publisher</td>
<td>RSC publishing</td>
</tr>
<tr>
<td>Link to online version</td>
<td><a href="http://dx.doi.org/10.1039/C1CC12615F">http://dx.doi.org/10.1039/C1CC12615F</a></td>
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<tr>
<td>Item record/more information</td>
<td><a href="http://hdl.handle.net/10197/3010">http://hdl.handle.net/10197/3010</a></td>
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<tr>
<td>Publisher's version (DOI)</td>
<td>10.1039/C1CC12615F</td>
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Tunable single-site ruthenium catalysts for efficient water oxidation†

Lucile Bernet,a Ralte Lalrempuia,b Wadih Ghattasa, Helge Mueller-Bunza, Laura Vigarab, Antoni Llobetab and Martin Albrechtab

The catalytic water oxidation activity of mononuclear ruthenium complexes comprising a pyridine-functionalized abnormal triazolylidene ligand can be adjusted by modification of the triazolylidene substituents, which is readily achieved through click-type cycloaddition chemistry, affording some of the most active ruthenium catalyst known thus far for water oxidation (TONs > 400, TOFs close to 7000 h⁻¹).

Efficient water splitting is one of the grand challenges in current chemical research, aiming at disclosing new fuel technologies for covering the increasingly growing global energy needs. While catalysts for water reduction have been available for long time, efficient water oxidizing methodologies are much rarer. This lack is in part due to the high potential and molecular complexity that need to be overcome in order to accomplish the 4-electron transfer required to generate O₂ from H₂O.

The natural evolution of O₂ at the Mn₄ core of photosystem II has provided much stimulation for synthetic advances. Multinuclear systems, including clusters, have been implemented in an attempt to distribute the multielectron transfer over several active sites, thus lowering the number of accessible oxidation states needed for a given metal center. Mononuclear complexes, which may offer advantages such as facile ligand tunability and the deduction of structure-activity-relationships, have only recently been reported to be active in water oxidation. While in some cases, the accessibility of less usual oxidation states has been proposed, other systems introduced ligand cooperativity in order to accommodate the extra charges (and holes) during the catalytic cycle. Abnormal carbenes such as 1,2,3-triazol-5-ylidene may be particularly suitable for such cooperative behavior, as these ligands feature a pronounced mesoionic resonance contribution that entails simultaneously electron accepting and donating properties.

The recent application of this ligand in the ruthenium-catalyzed base-free oxidation of alcohols may underpin this concept. Moreover, mononuclear iridium triazolylidene complexes have shown to be highly active in water oxidation, reaching turnover numbers (TONs) around 10.000. Here we report on the expansion of this approach to mononuclear ruthenium complexes containing an easily tunable chelating triazolylidene ligand functionalized with a pyridyl donor. Tailoring of the catalytic activity, still rare in water oxidation catalysis, is readily achieved by appropriate modification of the substituent at the triazolylidene nitrogens.

The triazolium salts used as carbene precursors were readily accessible via Cu-mediated [3+2] cycloaddition of azides and alkenes, and subsequent methylation at the triazole N3 position (Scheme 1).† The ruthenium complexes 2 were prepared from the corresponding pyridine-substituted triazolium salts 1 with AgOTf and subsequent transmetalation using [Ru(cymene)Cl]₂. The formation of the triazolylidene complexes 2 was indicated by NMR spectroscopy, which revealed the disappearance of the resonance around δH 8.5 assigned to the triazolium proton in 1 (CD₃CN solution). In the 13C NMR spectrum, the ruthenium-bound carbon appears around 172 ppm, corresponding to an approximate 20 ppm downfield shift as compared to the ligand precursor. The exact chemical shift is dependent on the substituent at nitrogen (δC 174.1, 172.9, 172.4, and 174.0 for 2a–2d, respectively), pointing to a moderate tunability of the electron density at this carbon via wingtip substitution. Chelation of the pyridine unit in solution is supported by the highfield resonance of the proton in the pyridine ortho position, which shifted from δH 8.4 in 1 to 9.4. The corresponding dicationic acetonitrile complexes 3 displayed similar spectroscopic characteristics for the bidentate triazolylidene ligand. Most diagnostic is the absence of the resonances due to the cymene ligand, and the upfield shift of the ortho-pyridine H to δH 9.1. In the 13C NMR spectrum, the ruthenium-bound carbon experiences a slight yet noticeable shift. In particular, the different sequence (δC 176.3, 174.5, 172.3, and 168.4 for 3a–3d, respectively) suggests some flexibility of the ligand in responding to the altered electronic environment at the ruthenium center in cationic 2 and dicatonic 3.

Evidence for the connectivity pattern in complexes 2 and 3 was obtained by X-ray crystallographic analyses.† The molecular structures of complexes 2a and 3a are representative and confirm the C,N-bidentate chelation of the ligand as deduced from solution

† Electronic Supplementary Information (ESI) available: Experimental procedures for ligands 1, and complexes 2 and 3, details on catalytic experiments, and crystallographic details for complexes 2a, 2b, 2c, 3a, 3b, 3c, 3d, 4, and 5. See http://www.rsc.org/suppdata/ja/b0/b000000x/

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studies (Fig. 1). While the Ru–C bond lengths fall within the expected 2.0–2.1 Å range,
and hence significantly shorter than in the monocationic complexes 2 (Ru–\text{triazolylidene} 2.028(7) Å). Likewise, the Ru–pyridine distance shrinks from 2.129(7) Å in 2 to 2.092(3) Å in 3. As a consequence of these bond length variations, the ligand bite angle is slightly larger (78.6(12) in 3 vs 76.59(6) in 2), though it remains rather acute. In complexes 3, the Ru–N\text{MCN} bonds transfers to the triazolylidene ligand average to 2.114(7) Å and are thus about 0.08 Å longer than the analogous bonds \text{trans} to the pyridine ligand (Ru–N 2.032(2) Å), reflecting the markedly stronger \text{trans} influence of the triazolylidene ligand as compared to pyridine.

Electrochemical analyses of the complexes revealed a quasi-reversible oxidation at 1.42 V (vs. SCE) for complexes 2 and at slightly lower potential for complexes 3 (Table 1). Analysis of the oxidation potentials demonstrates a close correlation between electron donor ability of the wingtip group and the ruthenium oxidation potential. Thus, complex 2d comprising a withdrawing Ph substituent displays the highest oxidation potential (\(E_{1/2} = 1.445\) V) and this potential decreases with increasing donor ability of the substituent R (\(E_{1/2} = 1.433\) V for R = Me, 1.427 for R = Et, and 1.425 for R = i-Pr). A different trend was observed in the dicaticonic complexes 3 with the oxidation potential increasing from Me < i-Pr < Ph < Si-electrochemical effects may become more dominant in these formally octahedral complexes. Accordingly, bulky substituents at the triazole nitrogen may interfere with the cis coordinating MeCN ligand, resulting in significant distortion from ideal octahedral geometry and thus reducing the ligands’ donor ability into relevant d orbitals. Such a model is further supported by solid-state analyses, which reveal that the angle between the pyridyl nitrogen and the \text{trans} coordinated MeCN (i.e. cis to the triazolylidene) deviates more distinctively in 3b and 3c than in 3a.

Complexes 2 and 3 were all active in the oxidation of water using Ce\text{IV} as sacrificial oxidant (Table 1). The cyanine-containing complexes 2 generated substantial amounts of CO\text{2} along with O\text{2} according to mass spectrometric analysis of the products. The relative CO\text{2} portion gradually increased over time, and was considerably higher with bulkier N-substituent, increasing in the order Me < Et < i-Pr < Ph. In contrast the corresponding dicaticonic complexes 3 produced O\text{2} exclusively. We therefore assume that cyanine rather than the carbene ligand is sensitive towards oxidation. Bulky wingtip groups induce steric congestion and thus tend to facilitate cyanine dissociation.

The dicaticonic complexes 3 are oxidatively stable, producing essentially no detectable CO\text{2}, and showing appreciable activity towards O\text{2} formation. Complex 3d is an exception and revealed small but noticeable quantities of CO\text{2}, which may be related to the propensity of N-bound phenyl groups to undergo cyclometalation.\textsuperscript{15} Complex 3a as the most active catalyst precursor of the series was further evaluated under different reaction conditions. At a 1:100 catalyst/oxygen ratio (1 mM catalyst), a marked reduction of catalyst performance was observed after about 10 turnovers, perhaps due to the formation of catalytically inactive dimeric species at high ruthenium concentrations. At a 1:10,000 catalysts/oxygen ratio (0.025 mM catalyst), the turnover numbers (TONs) increased substantially, reaching 105 mol O\text{2} per mol ruthenium after 45 min (i.e. 420 turnovers), and oxidation activity was still ongoing. Hence, catalyst deactivation is efficiently suppressed under dilute reaction conditions.

Catalytic runs at different concentrations indicate a linear relationship between the concentration and the initial turnover frequency, thus supporting homogeneous O\text{2} production at molecular catalytic sites rather than at aggregates. At an 8 mM complex concentration (1:100 catalyst/oxygen), initial turnover frequencies as high as 6660 h\textsuperscript{-1} were observed. These initial rates are amongst the highest for mono- and dimeric ruthenium complexes reported to date.\textsuperscript{17} In particular the methyl-substituted complexes 3a is about 100 times more active than previously tested pyridine- and phthalazine-based mononuclear ruthenium complexes.\textsuperscript{5,7} The overall TONs seem to correlate with the stereochemical effects deduced from chemical analyses and thus point to the relevance of electron donating groups for providing easy access to higher oxidation states.

Comparison of complex 3a with the homologous and sterically similar complex 4 comprising a normal imidazol-2-ylidene NHC ligand (Fig. 2) showed the latter complex to be a poor catalyst, providing significant quantities of CO\text{2} as well as low TONs and TOFs. These activity differences thus underline the advantageous role of the abnormal triazolylidene scaffold. Possibly, triazolylidene ligands may cooperatively assist bond cleavage and oxidation processes through reversible tautomerization of the mesoionic triazolylidene ruthenium aqua complex A to a carbene-
We thank the European Research Council (ERC-StG 208651) and Science Foundation Ireland, in parts under the Solar Energy Conversion Strategic Research Cluster, for funding.

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Notes and references
† The reaction of the pyridine-functionalized triazole with MeOTf was not chemoselective and gave mixtures of the triazolium and the pyridinium salt, indicated by the 1H NMR shift of the pertinent heterocyclic protons; they were separated by preparative TLC.
§ The DPV data for complex 3d suggest a more complex process than simple reversible metal oxidation.

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Ruthenium complexes comprising a broadly tunable triazolylidene ligand are efficient and robust water oxidation catalysts, producing \( \text{O}_2 \) exclusively and essentially no \( \text{CO}_2 \).