Manganese(III) Porphyrin-Catalyzed Dehydrogenation of Alcohols to form Imines, Tertiary Amines and Quinolines

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Manganese(III) Porphyrin-Catalyzed Dehydrogenation of Alcohols to form Imines, Tertiary Amines and Quinolines

Kobra Azizi, Sedigheh Akrami and Robert Madsen^{*[a]}

Abstract: Manganese(III) porphyrin chloride complexes have been developed for the first time as catalysts for the acceptorless dehydrogenative coupling of alcohols and amines. The reaction has been applied to the direct synthesis of imines, tertiary amines and quinolines where only hydrogen gas and/or water are formed as the byproduct(s). The mechanism is believed to involve the formation of a manganese(III) alkoxide complex which degrades into the aldehyde and a manganese(III) hydride species. The latter reacts with the alcohol to form hydrogen gas and thereby regenerates the alkoxide complex.

Introduction

Since the turn of the millennium, significant efforts have been devoted to the development of acceptorless dehydrogenative reactions with alcohols.^[1] In these transformations, a metal catalyst mediates the release of hydrogen gas to form the corresponding carbonyl compound, which can then undergo subsequent reactions in the same pot to generate other functional groups such as amines, imines, amides, carboxylic acids and esters. The transformations are usually catalyzed by complexes of precious metals where especially ruthenium and iridium compounds have been widely employed.^[1] In recent years, however, complexes based on the Earth-abundant metals iron, cobalt and manganese have surfaced as a new type of catalysts for the acceptorless dehydrogenations.^[2]

In fact, the first manganese complex was presented in 2016^[3] and since then many manganese-based catalysts have been developed for both the dehydrogenation^[2a-d,4] and the reverse hydrogenation reaction.^[2a-d,5] With one exception,^[6] although, they are all manganese(I) complexes stabilized by CO ligands which are not inexpensive since they are prepared from the costly carbonyl complex $\text{Mn}_2(\text{CO})_{10}$. Thus, it would be highly desirable to identify manganese complexes in the more common oxidation states for these dehydrogenative reactions.

Very recently, we presented the first manganese(III) complex for the acceptorless dehydrogenation of alcohols and elucidated the mechanism (Scheme 1).^[6] Notably, it is a salen complex, which is a known catalytic motif in organic chemistry, but for different reactions. The mechanism was investigated by experimental and theoretical methods and the reaction was

shown to proceed through the amido complex of the corresponding manganese(III) salen species (Scheme 1).^[6] This discovery raises the question whether other manganese(III) complexes with tetradentate ligands would also be able to catalyze acceptorless dehydrogenations?

Scheme 1. Manganese(III) salen-catalyzed alcohol dehydrogenation and the mechanism.

Manganese(III) porphyrin complexes and related compounds are well known for catalyzing oxidation reactions in the presence of a stoichiometric oxidant including hydroxylation/halogenation of alkanes, epoxidation of alkenes and oxidation of alcohols.^[7] The transformations involve catalytic cycles with various manganese(III), (IV) and (V) species.^[7] However, no dehydrogenation of a functional group with the release of hydrogen gas has been reported before with these complexes.

Herein, we describe the development of different manganese(III) porphyrin complexes for catalyzing the dehydrogenative coupling of alcohols and amines to form imines, tertiary amines and quinoline. In addition, the mechanism has been investigated indicating another pathway for the dehydrogenation than with the manganese(III) salen complexes. The findings underline the unique reactivity of manganese(III) complexes with tetradentate ligands in hydrogen gas-releasing transformations.

Results and Discussion

Benzyl alcohol and cyclohexylamine were selected as the substrates for the exploratory experiments where several manganese(III) (tetraaza)porphyrin chloride complexes were investigated for the dehydrogenation (Figure 1). Notably, the common and commercially available tetraphenylporphyrin (TPP) complex **A** gave a good conversion into the imine **1** in the absence of any additional additives (Table 1, entry 1). The

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influence of the substituents on the tetradentate ligand was then examined and the yield decreased with the corresponding *para*-carboxylate complex **B** (entry 2). Electron-donating groups, on the other hand, had a beneficial effect on the imine formation and a quantitative yield was obtained with both the *para*-methoxy complex **C** and the *para*-(diethylamino) compound **D** (entries 3 and 4). Slightly lower yields were observed with tetramesityl- and octaethylporphyrin complexes **E** and **F**, respectively, as well as with phthalocyanine complex **G** (entries 5 – 7). *Tert*-butyl groups on the tetraazaporphyrin ring, on the other hand, had a beneficial effect on the transformation and a quantitative yield was obtained with complex **H** (entry 8). Except for complex **B**, all the investigated (tetraaza)porphyrin complexes were fully soluble under the reaction conditions.

Figure 1. Structure of (tetraaza)porphyrin complexes used in the investigation.

Thus, the most promising results were achieved with complexes **C**, **D** and **H** and several experiments were performed to lower the loading, the reaction time and the temperature. With 3% of the catalysts and a 48 h reaction time, complex **H** still gave a quantitative yield of **1** while **C** and **D** furnished around 90% yield (entries 9 – 11). With 2% of the catalysts, complex **H** afforded 92% yield while lower yields were again obtained with

C and **D** (entries 12 – 14). These results point towards complex **H** as the preferred catalyst for the dehydrogenation. Lowering the loading further to 1% gave a moderate yield of the imine and the same was observed when the reaction was performed in refluxing toluene (entries 15 and 16). Surprisingly, additives such as inorganic bases, phosphines and amines had essentially no impact on the transformation (see Table S1 in the supporting information). Hence, an optimized protocol has been developed where equimolar amounts of alcohol and amine are reacted with 2% of complex **H** in refluxing mesitylene to afford the corresponding imine.

Table 1. Optimizing manganese(III)-catalyzed alcohol dehydrogenation.^[a]

Entry	X	Catalyst	t [h]	Yield [%] ^[b]
1	5	A	60	90
2	5	B	60	55
3	5	C	60	100
4	5	D	60	100
5	5	E	60	85
6	5	F	60	94
7	5	G	60	83
8	5	H	60	100
9	3	C	48	88
10	3	D	48	90
11	3	H	48	100
12	2	C	48	76
13	2	D	48	83
14	2	H	48	92
15	1	H	48	68
16 ^[c]	5	H	48	50

[a] Reaction conditions: BnOH (1 mmol), CyNH₂ (1 mmol), catalyst (0.0X mmol), tetradeane (0.5 mmol, internal standard), 4Å MS (150 mg), mesitylene (4 mL), reflux. [b] Determined by GC. [c] In toluene at reflux.

This new method was then applied to several different alcohols and amines to explore the substrate scope of the transformation (Table 2). First, various alcohols were reacted with cyclohexylamine and the products were isolated by flash chromatography. This afforded a 85% yield of **1** with the parent benzyl alcohol while *p*-methyl- and *p*-(*tert*-butyl)benzyl alcohol gave 89 and 90% yield, respectively, of **2** and **3**. The electronic

properties of the *para* substituent had very little influence on the imination since both electron-donating (as methoxy and methylthio) and electron-withdrawing groups (as halides, trifluoromethyl and methoxycarbonyl) gave very similar yields of the products **4** – **10**. Notably, no competing dehalogenation was observed with the *p*-chloro, *p*-bromo and *p*-iodo substrates. The only exception was *p*-nitrobenzyl alcohol, which furnished imine **11** in a moderate yield of 62% due to a concomitant reduction of the nitro group to give *N*-(*p*-aminobenzylidene)cyclohexylamine as a byproduct. *Ortho* substituted substrates gave a slightly lower yield than the corresponding *para* compounds as seen for *o*-methyl, *o*-chloro- and *o*-bromobenzyl alcohol which afforded imines **12** – **14** in 72 – 82% yield. 1-Naphthalenemethanol, on the contrary, gave a higher 88% yield of the resulting imine **15**.

Table 2. Imine formation from different alcohols and amines.^[a]

[a] Reaction conditions: Alcohol (1 mmol), amine (1 mmol), **H** (0.02 mmol), 4Å MS (150 mg), mesitylene (4 mL), reflux, 48 h (isolated yields).

Changing the amine to benzylamine gave 92% yield of **16** with benzyl alcohol while slightly lower yields of imines **17** – **19** were obtained with *o*-chloro, *o*-bromo- and 2,4,6-trimethylbenzyl alcohol. In the latter three cases, homocoupling of benzylamine to generate **16** was observed as a side reaction. The more hindered amines 1-adamantylamine and benzhydrylamine gave the corresponding imines **20** and **21** in 76 and 62% yield, respectively. The transformation could also be applied to arylamines where aniline afforded 80% yield of **22** in the reaction with benzyl alcohol. In addition, the imination could be performed with the aliphatic alcohol hexan-1-ol to give imine **23** in the reaction with benzylamine. Although full conversion of the alcohol was achieved, the isolated yield was only 43%, which is due to the instability of **23** towards hydrolysis during the purification. When the crude reaction mixture was analyzed by NMR, the yield of **23** was determined to be 72% by comparison with an internal standard and after removing the catalyst.

The evolution of hydrogen gas was confirmed by performing the reaction in Table 1, entry 14 in a closed two-chamber system^[8] where the other compartment contained diphenylacetylene and Pd/C in methanol. This experiment showed reduction of diphenylacetylene to (*Z*)-stilbene after full conversion into the imine and verifies the dehydrogenative pathway of the imine formation. When the experiment in Table 1, entry 14 was carried out with PhCD₂OH instead of PhCH₂OH, the only product formed was PhCD=N-Cy with no hydrogen incorporation into the benzylic position. This may indicate that the dehydrogenation takes place by a monohydride pathway and a metal-dihydride compound is not formed. Radical species do not appear to be part of the mechanism since addition of 2 equiv. of the scavengers 2,4-diphenyl-4-methylpent-1-ene and cyclohexa-1,4-diene had no influence on the conversion into the imine under the optimized conditions in Table 1, entry 14. The two scavengers were not converted during the transformations suggesting that the catalyst is unable to mediate the hydrogenation of olefins.

Table 3. Optimizing alkylation of secondary amine into tertiary amine.^[a]

$\text{Ph-CH}_2\text{OH} + \text{Me-NH-Ph} \xrightarrow[\substack{\text{mesitylene} \\ 4\text{\AA MS} \\ 164^\circ\text{C}, 48 \text{ h}}]{\substack{\text{X\% Catalyst} \\ 20\% \text{ Additive}}} \text{Ph-CH}_2\text{-N(Me)-Ph} + \text{H}_2\text{O}$ <p style="text-align: center;">24</p>					
Entry	X	Catalyst	Additive	Conversion of BnNHMe [%]	Yield [%] ^[b]
1	3	A	-	80	70
2	3	C	-	82	68

3	3	H	-	85	65
4	3	A	K ₂ CO ₃	100	88
5	3	C	K ₂ CO ₃	100	81
6	3	H	K ₂ CO ₃	100	80
7	2	A	K ₂ CO ₃	100	81
8 ^[c]	3	A	K ₂ CO ₃	100	93

[a] Reaction conditions: BnOH (1 mmol), BnNHMe (1 mmol), catalyst (0.0X mmol), additive (0.2 mmol), tetradecane (0.5 mmol, internal standard), 4Å MS (150 mg), mesitylene (4 mL), reflux, 48 h. [b] Determined by GC. [c] With 1.2 mmol of BnOH.

Dehydrogenative reactions between alcohols and amines can also be performed with secondary amines where the product is a tertiary amine. This transformation has been demonstrated with a variety of alcohols and amines when ruthenium,^[9] iridium,^[10] palladium^[11] and iron^[12] catalysts are employed. With manganese, however, only a special example exists with a manganese(I) catalyst where activated aromatic compounds are aminomethylated with methanol and secondary amines.^[13] Thus, benzyl alcohol and *N*-methyl benzylamine were selected as the starting substrates to investigate the alkylation where water is formed as the only byproduct. Interestingly, the reaction afforded the desired tertiary amine **24**, but complete conversion of the starting amine was not observed with 3% of complexes **A**, **C** and **H** (Table 3, entries 1 – 3). However, when K₂CO₃ was added as a basic additive, all three catalysts gave full conversion of the starting material (entries 4 – 6). The highest yield was observed with complex **A**, which seems to be the preferred catalyst in this case. Other additives were also investigated such as KO^tBu, Cs₂CO₃, Ca₃N₂, MgSO₄, NaHCO₃ and pyridine, but no improvements were observed (results not shown). Lowering the loading of **A** to 2% decreased the yield (entry 7) while a slightly higher yield was obtained by increasing the amount of the alcohol to 1.2 equiv. (entry 8). These final conditions were selected for general use and applied to different alcohols and amines where the products again were isolated by flash chromatography (Table 4).

Table 4. Synthesis of tertiary amines from alcohols and secondary amines.^[a]

[a] Reaction conditions: Alcohol (1.2 mmol), amine (1 mmol), **A** (0.03 mmol), K₂CO₃ (0.2 mmol), 4Å MS (150 mg), mesitylene (4 mL), reflux, 48 h (isolated yields).

The transformation afforded a 78% isolated yield of the parent compound **24** while *p*-methoxy- and *p*-chlorobenzyl alcohol gave 82 and 70% yield, respectively, of **25** and **26** in the reaction with *N*-methyl benzylamine. In the same reaction, *p*-nitrobenzyl alcohol provided the tertiary amine **27** in a moderate yield of 52% due to several byproducts whereas 2,4-dimethylbenzyl alcohol furnished the corresponding amine **28** in 67% yield. *N*-Ethyl benzylamine gave the same yields as the *N*-methyl analogue in the reaction with benzyl and *p*-methoxybenzyl alcohol to afford **29** and **30**. *N*-Methyl *p*-methylbenzylamine produced 80% yield of both **31** and **32** in the reaction with the two alcohols while the alkylation of *N*-methyl *m*-methylbenzylamine with benzyl alcohol resulted in **33** in 73% yield. Benzyl and *p*-methoxybenzyl alcohol were also reacted with *N*-methyl *p*-bromobenzylamine, *N*-methyl *m*-chlorobenzylamine, *N*-(*p*-methylbenzyl) *p*-methoxybenzylamine and *N*-ethyl *p*-(trifluoromethyl)benzylamine where the products **34** – **41** were isolated in 58 – 86% yield. Tribenzylamine (**42**) was obtained in 75% yield upon reaction between dibenzylamine and benzyl alcohol while *N*-allyl benzylamine was *N*-benzylated to give **43** in 62% yield without any accompanying reduction of the olefin. In the same way, piperidine and morpholine were *N*-benzylated to afford **44** and **45** in 70 and 66% yield whereas the arylamines *N*-ethylaniline and tetrahydroquinoline underwent the benzylation to provide **46** and **47** in only 47 and 35% yield, respectively. In the latter case, tetrahydroquinoline was converted into quinoline as a side reaction while *N*-ethylaniline did not undergo complete conversion in the transformation. Thus, the nucleophilicity of the amine influences the alkylation resulting in lower yields with less nucleophilic substrates. The aliphatic alcohol hexan-1-ol was also investigated, but a very poor conversion was observed in the reaction with *N*-methyl benzylamine (result not shown).

Besides the dehydrogenation of tetrahydroquinoline, the quinoline framework can also be prepared by a dehydrogenative coupling between *o*-aminobenzyl alcohols and secondary alcohols. The condensation between the corresponding carbonyl compounds is known as the Friedländer quinoline synthesis, but often suffers from a moderate yield due to the limited stability of *o*-aminobenzaldehydes and undesired aldol condensations.^[14] These side reactions occur to a lower degree in the dehydrogenative quinoline synthesis from alcohols, which has previously been catalyzed by different ruthenium and iridium complexes (0.025 – 0.5% loading at 110 °C)^[15] as well as various copper, nickel, cobalt and manganese(I) compounds (2 – 10% loading at 90 – 150 °C).^[16] All the transformations are carried out in the absence of a hydrogen acceptor, but 0.5 – 3 equiv. of a base is required such as KOH or KO^tBu.^[15,16]

To develop a new manganese(III)-catalyzed quinoline synthesis, several exploratory experiments were first performed with equimolar amounts of *o*-aminobenzyl alcohol and 1-phenylethanol in the presence of complex **A** (Table 5). It was quickly realized that K₂CO₃ was not a sufficiently strong base in

this case since it only gave 2-phenylquinoline (**48**) in 9% yield (entry 1) while KOH, NaOH and KO^tBu afforded 21 – 32% yield (entries 2 – 4). Combining KOH and KO^tBu gave an improved outcome (entry 5) and especially when the reaction time was extended (entry 6). A further increase in the yield was obtained upon adding a small amount of pyridine as an additional base (entry 7) and with 1.5 equiv. of 1-phenylethanol the target quinoline was produced in 76% yield (entry 8). No improvement was observed by further increasing the amount of 1-phenylethanol (entry 9) while the yield decreased with lower amounts of complex **A** (entry 10) or with only one of the inorganic bases (entries 11 and 12). Thus, an optimized protocol has been established where quinolines are prepared by reacting *o*-aminobenzyl alcohols with 1.5 equiv. of secondary alcohols in the presence of 5% of complex **A** and a mixture of KOH, KO^tBu and pyridine.

Table 5. Optimizing dehydrogenative quinoline synthesis.^[a]

Entry	X	Additive	t [h]	Yield [%] ^[b]
1	1	K ₂ CO ₃ (2 mmol)	48	9
2	1	KOH (2 mmol)	48	32
3	1	NaOH (2 mmol)	48	27
4	1	KO ^t Bu (2 mmol)	48	21
5	1	KOH (2 mmol), KO ^t Bu (2 mmol)	48	37
6	1	KOH (2 mmol), KO ^t Bu (2 mmol)	60	50
7	1	KOH (2 mmol), KO ^t Bu (2 mmol), pyridine (0.2 mmol)	60	62
8	1.5	KOH (2 mmol), KO ^t Bu (2 mmol), pyridine (0.2 mmol)	60	76
9	2	KOH (2 mmol), KO ^t Bu (2 mmol), pyridine (0.2 mmol)	60	75
10 ^[c]	1.5	KOH (2 mmol), KO ^t Bu (2 mmol), pyridine (0.2 mmol)	60	58
11	2	KOH (2 mmol)	60	53
12	2	KO ^t Bu (2 mmol)	60	43

[a] Reaction conditions: *o*-Aminobenzyl alcohol (1 mmol), 1-phenylethanol (X mmol), **A** (0.05 mmol), additive, tetradecane (0.5 mmol, internal standard), 4Å MS (150 mg), mesitylene (4 mL), reflux. [b] Determined by GC. [c] With 3% of **A**.

The substrate scope of this new procedure was then investigated with a variety of alcohols and the products were isolated by column chromatography (Table 6). In this way, 2-phenylquinoline (**48**) was obtained in 70% yield while the

corresponding 2-(*p*-tolyl) compound **49** was formed in 90% yield. 1-(*p*-Methoxyphenyl)- and 1-(*p*-methylthiophenyl)ethanol reacted with *o*-aminobenzyl alcohol to give quinolines **50** and **51**, respectively, in 93 and 82% yield. In the same reaction, 1-(*p*-fluorophenyl)-, 1-(*o*-chlorophenyl)- and 1-(*p*-bromophenyl)ethanol gave the related quinolines **52** – **54** in 78 – 87% yield while a slightly lower yield was obtained of 2-(*p*-iodophenyl)quinoline (**55**) due to partial dehalogenation. Similar reactions were carried out with 2-amino-4-chlorobenzyl alcohol which reacted with 1-phenyl-, 1-(*p*-tolyl)-, 1-(*p*-methoxyphenyl)- and 1-(*p*-fluorophenyl)ethanol to give the corresponding 2-aryl-7-chloroquinolines **56** – **59** in 62 – 82% yield. Again, a more modest result was obtained with 1-(*p*-iodophenyl)ethanol giving 7-chloro-2-(*p*-iodophenyl)quinoline (**60**) in 53% yield due to some dehalogenation. The transformation could also be performed with cyclohexanol and cycloheptanol to afford tricyclic compounds **61** and **62**, respectively, in 48 and 56% yield. *p*-Nitro- and *p*-cyano-substituted 1-phenylethanol, on the other hand, failed to produce the desired quinolines, but instead a complex mixture was obtained (results not shown).

Table 6. Synthesis of quinolines from *o*-aminobenzyl alcohols and secondary alcohols.^[a]

[a] Reaction conditions: *o*-Aminobenzyl alcohol (1 mmol), secondary alcohol (1.5 mmol), **A** (0.05 mmol), pyridine (0.2 mmol), KOH (2 mmol), KOtBu (2 mmol), 4Å MS (150 mg), mesitylene (4 mL), reflux, 60 h (isolated yields).

To gain more information about the mechanism several experiments were performed to investigate the fate of the porphyrin complex during the reaction. LCMS analysis of the mixture after the imination in Table 1, entry 1 showed only porphyrin complex **A** and no compounds with a reduced ligand could be detected, i.e. the corresponding chlorin or bacteriochlorin complexes. Complex **A** could be recovered in 70% yield and used again in the same reaction although the yield then decreased to 58%. When the experiment was carried out with PhCD₂OH and CyNH₂, 1 – 4 deuterium atoms were incorporated into complex **A**. This must be in the β -pyrrolic positions, which was confirmed by isolating the complex, subjecting it to demetallation with acid and analyzing the ligand by NMR spectroscopy. On the other hand, when the imination with PhCD₂OH and CyNH₂ was carried out with complex **F**, no deuterium incorporation occurred in the porphyrin ring. Thus, a hydrogen – deuterium scrambling is possible in the β -positions of the porphyrin by using PhCD₂OH as the substrate, but no incorporation occurs in the meso positions.

The main structural feature of the porphyrin ring is the aromatic 18 π -electron conjugated network. Two pyrrole double bonds in the β -positions are not part of this system and these two bonds are susceptible to hydrogenation to afford the chlorin and the bacteriochlorin structure.^[17] On the contrary, these hydroporphyrins are rather easily oxidized back to the parent porphyrin macrocycle. It seems inconceivable that PhCD₂OH coordinates to manganese and transfers deuterium to the β -positions in a similar way as the reduction of the Schiff bases in the salen complexes.^[6] It also appears highly unlikely that the 18 π -electron pathway is disrupted during the process since this usually requires very strong nucleophiles such as organolithium reagents.^[18] Therefore, the most reasonable explanation for the deuterium introduction is a partial reduction of the porphyrin ring by an external reducing agent in the mixture. To test this scenario complex **A** was treated with NaBH₄ and NaBD₄ in two separate experiments in DMSO at 120 °C. In both cases, the manganese(III) chlorin complex could be detected by LCMS analysis of the mixture. However, after workup only the porphyrin complex was isolated which is presumably due to aerobic oxidation of the chlorin compound. In the experiment with NaBD₄ some incorporation of deuterium occurred into the porphyrin framework and again it was confirmed by NMR to be in the β -pyrrolic positions. This experiment shows that a

reducing agent is able to react with the porphyrin ring and result in deuterium incorporation.

Another experiment was designed by using a closed system with two connected reaction vessels and a balloon. The imination with PhCH_2OH , CyNH_2 and complex **A** (Table 1, entry 1) was carried out in the first vessel while in the second vessel (with the balloon attached) DCI in D_2O was added to zinc metal.^[19] This liberated D_2 in the second vessel, which was transferred to the first vessel. Subsequent analysis of complex **A** after the imination reaction revealed deuterium incorporation into the complex while no isotope insertion occurred in the alcohol or the imine. This again indicates that reduction of the porphyrin takes place by a reducing agent in the mixture (such as a metal hydride) and not directly by the alcohol.

Thus, manganese(III) porphyrin complexes with axial hydride and alkoxide ligands are most likely formed as intermediates in the reaction. To the best of our knowledge such complexes have not previously been structurally characterized.^[20,21] To gain some experimental evidence for the formation of these complexes, an experiment was carried out where complex **A** (1 mmol) was mixed with BnOH (50 mmol) and NaH (10 mmol) in mesitylene. After stirring for 30 min at room temperature LCMS analysis of the mixture showed complete conversion of complex **A** into the benzyloxy complex $(\text{TPP})\text{Mn}^{\text{III}}(\text{OBn})$. The mixture was then slowly heated to 180°C with a distillation head attached which resulted in 3 mmol of a 6:1 mixture of benzyl alcohol and benzaldehyde distilling off from the reaction. GC analysis of the residue showed benzyl alcohol and small amounts of benzaldehyde. This test illustrates that a manganese(III) alkoxide complex can undergo degradation with the formation of the aldehyde (and most likely the corresponding manganese(III) hydride complex).

Based on these observations we believe the most probable mechanism involves initial formation of the alkoxide complex **63** (Scheme 2). No coordination site is available in this compound for a classical β -hydride elimination. However, a related rhodium(III) porphyrin complex was shown to react with isopropanol to produce acetone and the rhodium(III) hydride species^[22] although the exact mechanism for this reaction is not known.^[23] In addition, $(\text{TPP})\text{Rh}^{\text{III}}\text{Cl}$ was shown to mediate the photocatalytic conversion of secondary alcohols into ketones and hydrogen gas.^[24] Therefore, we contemplate that alkoxide complex **63** can be converted into the aldehyde and hydride complex **64** in refluxing mesitylene.^[25] Subsequent reaction with the alcohol regenerates complex **63** and forms hydrogen gas. This is a different mechanistic pathway than elucidated for the manganese(III) salen-catalyzed alcohol dehydrogenation in refluxing toluene (Scheme 1).^[6] The higher temperature needed for the porphyrin-catalyzed protocol is most likely due to the conversion of the alkoxide complex **63** into the hydride species **64**.

Scheme 2. Proposed mechanism for acceptorless alcohol dehydrogenation.

Conclusions

In summary, manganese(III) porphyrin complexes have been shown to catalyze the dehydrogenation of alcohols with the release of hydrogen gas. The transformation has been applied to the direct synthesis of imines, tertiary amines and quinolines from alcohols and amines. The reactions are believed to proceed through a porphyrin manganese(III) alkoxide complex as the intermediate. Experimental studies have indicated that this complex can degrade with the formation of the aldehyde and most likely the corresponding hydride complex. Subsequent reaction between the latter and the alcohol forms hydrogen gas and regenerates the alkoxide complex. This constitutes the second example of a manganese(III) catalyst for the acceptorless dehydrogenation of alcohols, but contrary to the first example with a salen complex the porphyrin complexes react by a different mechanism.

Experimental Section

General procedure for imine synthesis: An oven-dried tube (20 mL) was charged with complex **H** (12 mg, 0.02 mmol) and pre-activated 4Å molecular sieves (150 mg). The tube was placed in a Radley carousel on a hotplate, subjected to vacuum and then filled with N_2 (repeated 3 times). Freshly degassed mesitylene (4 mL) was injected into the mixture followed by heating to 164°C under a N_2 atmosphere. Then, the alcohol (1 mmol), the amine (1 mmol) and tetradecane (0.5 mmol, internal standard) were added to the blue solution and the reaction was refluxed for 48 h. The mixture was purified directly by silica gel column chromatography (hexane/ Et_3N , 98:2) to obtain the desired product.

General procedure for tertiary amine synthesis: Complex **A** (20 mg, 0.03 mmol), K_2CO_3 (20 mg, 0.2 mmol) and pre-activated 4Å molecular sieves (150 mg) were placed in an oven-dried tube (20 mL). The tube was placed in a Radley carousel on a hotplate, subjected to vacuum and then filled with N_2 (repeated 3 times). Freshly degassed mesitylene (4 mL) was injected into the mixture followed by heating to 164°C under a N_2 atmosphere. Then, the alcohol (1.2 mmol), the amine (1 mmol) and tetradecane (0.5 mmol, internal standard) were added to the green solution and the reaction was refluxed for 48 h. The mixture was purified

directly by silica gel column chromatography (hexane/Et₃N, 98:2) to obtain the desired product.

General procedure for quinoline synthesis: Complex **A** (35 mg, 0.05 mmol), 2-aminobenzyl alcohol (1 mmol), KOH (2 mmol), KO^tBu (2 mmol) and pre-activated 4Å molecular sieves (150 mg) were placed in an oven-dried tube (20 mL). The tube was placed in a Radley carousel on a hotplate, subjected to vacuum and then filled with N₂ (repeated 3 times). Freshly degassed mesitylene (4 mL) was injected into the mixture followed by heating to 164 °C under a N₂ atmosphere. Then, the secondary alcohol (1.5 mmol), pyridine (0.2 mmol) and tetradecane (0.5 mmol, internal standard) were added to the green solution and the reaction was refluxed for 60 h. The mixture was concentrated and the residue purified by silica gel column chromatography (CH₂Cl₂/hexane, 1:1) to obtain the desired product.

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Keywords: alcohols • dehydrogenation • homogeneous catalysis • manganese • synthetic methods

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**Manganese(III) Porphyrin-Catalyzed
Dehydrogenation of Alcohols to form
Imines, Tertiary Amines and
Quinolines**

Three times manganese(III): Manganese(III) porphyrin complexes catalyze the dehydrogenative coupling between alcohol and amines to generate imines, tertiary amines and quinolines. Manganese(III) alkoxide and hydride complexes are believed to be the catalytically active species responsible for the hydrogen gas release.