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REGULAR ARTICLE

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Manganese-salen catalyzed oxidative benzylic chlorination

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Abstract. Metalloporphyrins are well-known to serve as the model for mimicking reactivities exhibited by cytochrome P450 hydroxylase. Recent developments on selective C–H halogenation using Mn-porphyrins provided the way for understanding the reactivity as well as mechanism of different halogenase enzymes. In this report, we demonstrated a method for benzylic C–H chlorination using easily prepared Mn(salen) complex as the catalyst, which shows a complementary reactivity of Mn-porphyrins. Here, NaOCl has been used as a chlorinating source as well as the oxidant. Efforts towards understanding the mechanism suggested the formation of the high-valent Mn(V)=O species which is believed to be the key intermediate to conduct this transformation.

Keywords. High-valent manganese; salen; hypochlorite; benzylic chlorination.

1. Introduction

Nature has developed several fascinating enzymatic path to incorporate hydroxyl or halogen group oxidizing specific C–H bond of bioactive molecules.[1] In this perspective, heme-dependent enzymes such as cytochrome P450, haloperoxidase are known to accomplish hydroxylation and halogenation in natural molecules[2] where a high-valent iron-oxo species is believed to be the active intermediate.[1,3] In the realm of practical chemistry, the feasibility of halogenation *viz.* chlorination of benzylic substrates is a bit challenging because of the competitive ring halogenation or over-halogenation. The reported procedures for benzylic sp^3 C–H chlorination uses reagents such as free Cl_2,[4] PCl_5,[5] aquaregia,[6] Et_4NCl,[7] benzyltrimethylammonium tetrachloroiodate $BTMAICl_4$,[8] nano-Ag/AgCl,[9] ^{t}BuOCl,[10] *etc.,* which are explosive, toxic as well as corrosive. Further, most of the cases require irradiation or heating resulting in poor chemoselectivity and regioselectivity. Additionally, use of nano-Ag/AgCl,[9] ^{t}BuOCl[10] for chlorination purpose produced oxygenated side product in major quantity. To address these issues, researchers designed various metalloporphyrin as biocatalyst which successfully served as a model compound to mimic the reactivities of cytochrome P450 over the past few decades.[11] Among the various known metalloporphyrins, Mn-porphyrins have been known for its incredible reactivity towards the oxidation of both saturated and unsaturated hydrocarbons including oxidation of complex molecules.[12] Recently, Mn-porphyrin complexes had also shown its ability to catalyze carbon-halogen bond formation (Scheme 1a).[13] Pertaining to chlorination, in 2010, J. T. Groves and co-workers demonstrated Mn-porphyrin mediated C–H bond chlorination of simple hydrocarbons which depicted only single instance of benzylic chlorination.[13a] Herein, we are interested to investigate the less explored domain of benzylic sp^3 C–H chlorination using a manganese salen complex as catalyst (Scheme 1b). This catalyst was mainly developed by Jacobson/Katsuki for enantioselective epoxidations.[14] It has also been utilized effectively towards other carbon-heteroatom bond formations.[15] The attractive features of these catalysts lie in their easy synthesis and facile structural modifications.

Chlorinated benzylic compounds are very important class of substrates since their chloromethyl group can be easily converted to other group like hydroxymethyl, cyanomethyl, *etc.*[16] Further, various bioactive molecules, such as ibuprofen, vitamin E analogues like steroids, terpenoids including various amino acids contain benzylic position that are amenable for late-stage diversification (Figure 1).

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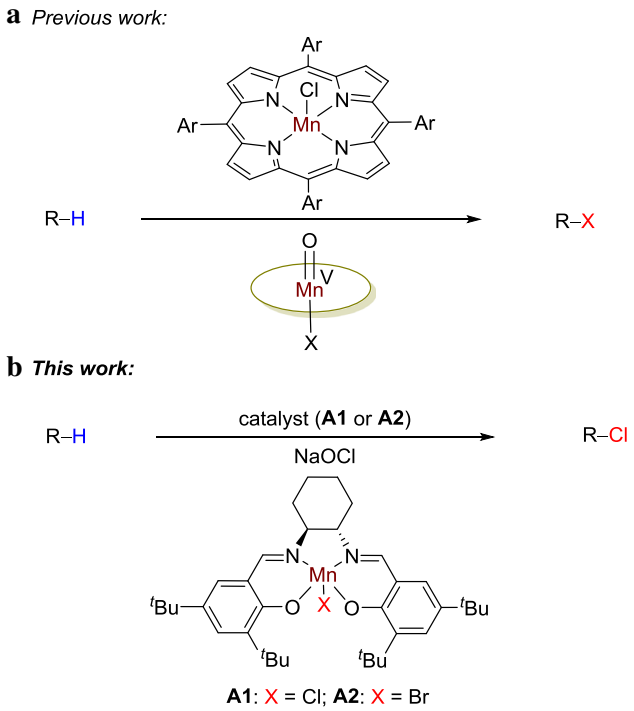
Electronic supplementary material: The online version of this article (https://doi.org/10.1007/s12039-018-1511-7) contains supplementary material, which is available to authorized users.



Scheme 1. (a) Mn-porphyrine catalyzed C–H halogenation. (b) Mn-salen catalyzed benzylic C–H chlorination.

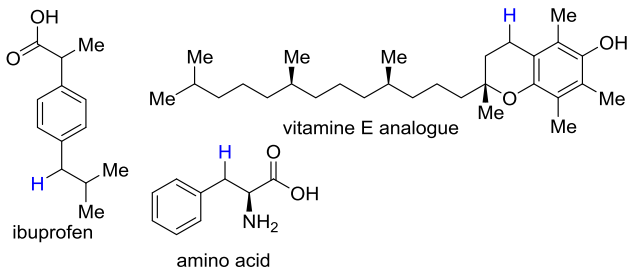


Figure 1. Examples of bioactive molecules containing benzylic C–H bond.

2. Experimental

2.1 *Materials and instrumentation*

Unless otherwise stated, all of the reactions were carried out at room temperature in a 10 mL screw-capped reaction tube under N_2 atmosphere. NaOCl was purchased from Sigma Aldrich. Other necessary Chemicals and solvents were purchased from Sigma Aldrich, Merck, Alfa Aesar and Spectrochem. A gradient elution using petroleum ether and ethyl acetate was performed, based on Merck Aluminum TLC sheets (silica gel 60F254). Products were characterized by ^{1}H and ^{13}C NMR spectroscopy, gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS). *n*-decane was used as standard. NMR spectra were recorded either on a Bruker 500/400 MHz or on a Varian 400 MHz instrument. Copies of the ^{1}H, ^{13}C spectra are included in Supporting Information. All ^{1}H NMR spectra were reported in units of parts per million (ppm) and measured relative to the signals for residual chloroform (7.26 ppm) in a deuterated solvent, unless otherwise stated. All ^{13}C NMR spectra were reported in ppm relative to $CDCl_3$ (77.23 ppm), unless otherwise stated, and all were obtained with ^{1}H decoupling. All the products were analyzed by GC-MS. GC-MS was performed on a Thermo Scientific ISQ QD Mass Spectrometer attached with Thermo Scientific TRACE 1300 gas chromatograph using an HP-5ms capillary column (30 m × 0.25 mm × 0.25 μm, J&W Scientific) with helium as the carrier gas All GC analyses were performed on an Agilent 7890A GC system with a flame ionization detector using a J&W DB-1 column (10 m × 0.1 mm, i.d.). UV-Vis studies were performed in Agilent 8453 diode array based UV-Vis Spectrophotometer. ESI-MS spectra were performed in Bruker QTOF ESI-MS instrument. First order rate constants ($k1$) were calculated based on non-linear exponential fit in OriginPro8 software. Single crystal of complex **A2** was diffracted in Rigaku X-ray single crystal diffractometer. The EPR measurements were carried out with an X-band (9.5 GHz) Bruker EMX Plus at 100 K.

2.2 *Synthesis of salen ligand (H_2Salen)*

Derivative of Salisaldehyde (2 equiv.) as solid was added in portions to absolute ethanol solution of diamine derivative. The reaction mixture was heated to reflux for an hour under nitrogen atmosphere and then cooled to room temperature.[17] The yellow colored product was then collected by filtration washed with cold ethanol and dried under vacuum.

2.2a *N,N-bis(3,5-di-tert-butylsalicylidene)-1,2-cyclohexanedi-amine*: ^{1}H NMR (500 MHz, $CDCl_3$) δ 13.70 (s, 2H), 8.29 (s, 2H), 7.30 (d, J = 2.5 Hz, 2H), 6.98 (d, J = 2.5 Hz, 2H), 5.04–4.91 (m, 2H), 3.35–3.29 (m, 2H), 1.94 (d, J = 14.5 Hz, 2H), 1.90–1.84 (m, 2H), 1.73 (d, J = 11.0 Hz, 2H), 1.50–1.45 (m, 2H), 1.41 (s, 18H), 1.23 (s, 18H).^{13}C NMR (101 MHz, $CDCl_3$) δ 166.0, 158.2, 140.0, 136.5, 126.9, 126.2, 118.0, 72.6, 35.1, 34.2, 33.4, 31.6, 29.6, 24.5.

2.3 *Synthesis of Mn(salen) complex (Mn^{III}(salen)X)*[17]

H_2salen ligand (1.6 mmol) in 10 ml of toluene was added to a suspension of $Mn(OAc)_2.4H_2O$ (3 equiv., 5 mmol) in 20 mL of boiling ethanol. Then the reaction mixture was refluxed overnight under nitrogen. After passing a stream of air through the reaction mixture. 20 mL saturated aqueous NaCl or KBr solution was added under vigorous stirring and the reaction mixture was allowed to cool at room temperature. After addition of 100 mL of toluene and 20 mL CH_2Cl_2, the organic layer was extracted with water and saturated NaCl solution. Then, it was dried with Na_2SO_4. Then the solvent was evaporated under reduced pressure. The product was dissolved in CH_2Cl_2 and then collected by filtration as a brown powder and dried under vacuum. The complex was characterized by X-ray crystallography (**A2**), ESI-MS

study (m/z = 599.3 for $C_{36}H_{52}MnN_2O_2$) (**A1/A2**) and UV-Vis spectroscopy (λ_{max} = 440 nm and 510 nm) (**A1/A2**).

2.4 *General procedure for benzylic chlorination*

NaOCl (0.66 M, 4 mL) was added to a solution of [Mn(Salen)X] (2 mol%) catalyst, tetrabutylammonium chloride (TBACl, 5 mol%), substrate (2 mmol) in dichloromethane in a 10 mL sealed vial. Here, TBACl acts as phase transfer catalyst and NaOCl is oxidant and chlorinating source. This mixture was stirred smoothly under a nitrogen atmosphere at room temperature and carried out for 12 h. Then the reaction mixture was extracted with CH_2Cl_2 and water to remove the catalyst and unreacted NaOCl. The solution was analyzed by GC/MS. The yield was calculated with respect to reactant added.

2.4a *Benzyl chloride (**2b**)*[18]: Compound **2b** was obtained from toluene **1b**, isolated by column chromatography (hexane/ether). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.40 (t, J = 5.4 Hz, 3H), 7.38–7.31 (m, 2H), 4.61 (s, 2H).

2.4b *1-bromo-4-(chloroethyl)-benzene (**2c**)*: Compound **2c** was obtained from 1-bromo-4-ethylbenzene **1c**, isolated by column chromatography (hexane/ethyl acetate). ^{1}HNMR (400 MHz, CDCl3) δ 7.48 (m, 2H), 7.3 (m, 2H), 5.04 (q, 1H), 1.83 (d, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.0, 131.1, 128.4, 122.3, 58.0, 26.6.

2.4c *4-(chloromethyl)-1,1′-biphenyl (**2d**)*: Compound **2d** was obtained from 4-methyl-1,1′-biphenyl **1d**, isolated by column chromatography (hexane/ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65–7.58 (m, 4H), 7.51–7.45 (m, 4H), 7.38 (ddd, J = 7.3, 3.8, 1.1 Hz, 1H), 4.66 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.6, 140.7, 136.7, 129.3, 129.0, 127.7, 127.7, 127.3, 46.3.

2.4d *4′-methyl-[1,1′-biphenyl]-2-carbonitrile (**2e**)*: Compound **2e** was obtained from 4′-methyl-[1, 1′- biphenyl]-2-carbonitrile **1e**, isolated by column chromatography (hexane/ethyl acetate) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, J = 7.7 Hz, 1H), 7.72–7.61 (m, 2H), 7.59–7.54 (m, 2H), 7.52 (dd, J = 5.3, 3.0 Hz, 2H), 7.46 (td, J = 7.7, 1.1 Hz, 1H), 4.65 (s, 1H).^{13}C NMR (101 MHz, $CDCl_3$) δ 144.9, 138.4, 138.1, 134.0, 133.1, 130.2, 129.4, 129.3, 129.1, 128.0, 126.8, 118.8, 111.4, 45.9.

2.4e *(1-chloromethyl)naphthalene (**2f**)*: [19] Compound **2f** was obtained from 1-methyl naphthalene **1f**, isolated by column chromatography (hexane/ethyl acetate). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.16 (d, J = 8.4 Hz, 1H), 7.88 (dd, J = 17.0, 8.2 Hz, 2H), 7.61 (t, J = 7.6 Hz, 1H), 7.57–7.52 (m, 2H), 7.47–7.41 (m, 1H), 5.07 (s, 2H).

2.4f *(Chloromethylene)-dibenzene (**2g**)*: Compound **2g** was obtained from diphenyl methane **1g**, isolated by column chromatography (hexane/ethyl acetate) ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.44 (d, J = 7.5 Hz, 4H), 7.41–7.35 (m, 4H), 7.32 (q, J = 7.1 Hz, 2H), 6.16 (s, 1H).

2.4g *Methyl 2-(4-(1-chloro-2-methylpropyl)phenyl) propane (**4**)*: Compound **4** was obtained from ibuprofen methyl ester **3**, isolated by column chromatography (hexane/ethyl acetate). ^{1}H NMR (400 MHz, $CDCl_3$) δ ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31–7.28 (m, 2H), 7.28–7.25 (m, 2H), 4.62 (d, J = 7.6 Hz, 1H), 3.72 (q, J = 7.2 Hz, 1H), 3.66 (s, 3H), 2.22 (dq, J = 13.5, 6.7 Hz, 1H), 1.49 (d, J = 7.2 Hz, 3H), 1.10 (d, J = 6.6 Hz, 3H), 0.87 (d, J = 6.7 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.1, 140.3, 140.1, 127.9, 127.6, 70.7, 52.3, 45.3, 36.8, 20.4, 19.7, 18.7. HRMS [ESI, (+) ve]: calcd. for (C14H19ClNaO2) 277.0962, found 277.0966.

2.5 *Preparation of oxidized [Mn(salen)]$^+$ complex for ESI-MS and UV-Vis study*

In the CH_2Cl_2 solution of complex **A1/A2** (0.3×10^{-3} M), 50 fold of excess NaOCl was added and shaken vigorously at room temperature, after 15 s the color of the solution changed from orange-brown to green. Then, it was immediately subjected to UV-Vis spectroscopy. For ESI-MS study, to the CH_2Cl_2 solution of complex **A1** (10^{-3} M), 15 fold of excess NaOCl was added and shaken vigorously for a minute at room temperature, then directly used for ESI-MS study at a different time.

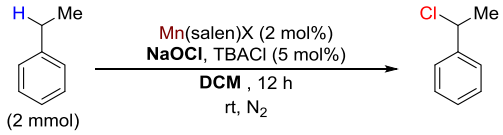
2.6 *Kinetic study*

A stock solution of complex **A2** (1.5×10^{-4} M) was prepared in CH_2Cl_2. To this solution 50 equivalent of excess NaOCl was added and shaken vigorously at 0 °C to get the green color solution. Then 4 mL of this solution was taken and 1 mmol of ethylbenzene was added and immediately subjected to time-dependent UV-Vis study. The spectra were recorded in every 5 s. The rate constant for decay of Mn(V)=O complex was determined from time trace at λ_{max}, 640 nm which shows an exponential decay pattern. Kinetic data analysis showed that this decay followed a pseudo-first order reaction in presence of excess substrate with decay rate constant $k_1 = 4.94 \times 10^{-2}$ s^{-1}.

2.7 *EPR study to detect the formation of Mn^{IV} (salen) complex*

A solution of Mn^{III}(salen) [complex **A1** (10 mM)] in 2.5 mL of CH_2Cl_2 was prepared. To this solution, 5 equiv. of PhIO was added and the solution was stirred for 5 min. When the colour of the solution changed from brown to dark green, 10 equiv. of ethylbenzene (substrate) was added. The solution was shaken for a few seconds and an aliquot of 250 μL of this solution was transferred to an EPR tube, frozen at 100 K and the EPR spectrum of this solution was recorded.

Table 1. Optimization of Mn-salen catalyzed benzylic C–H chlorination.



Entry	NaOCl amount (mL)	DCM amount (mL)	Yield (%)[a]	TON
1	0.5	1	2	1
2	1	1	8	4
4	1.5	1	6	3
5	2	1	10	5
6	2.5	1	12	6
7	3	1	12	6
8	3.5	1	14	7
9	**4**	**1**	**28**	**14**
10	5	1	22	11
11	4	2	12	6
12	4	3	16	8
13	4	4	17	8.5

[a]The yield of the product is determined by GC. TON (turn over number) for the catalyst is calculated as the mol of product formed per mol of catalyst used.

3. Results and Discussion

To check the efficacy of Mn(salen) complex towards benzylic sp^3 C–H chlorination, ethylbenzene was treated with *N*, *N*-bis(3,5-di-*tert*-butylsalicylidene)-1,2-cyclohexanediamino-manganese chloride **A1** as the catalyst and aqueous NaOCl solution (both as oxidant and chlorinating agent) in CH_2Cl_2. For this catalytic reaction tetrabutylammonium chloride (TBACl) was used as phase transfer catalyst. This biphasic system afforded 1-chloroethyl benzene with turn over number (TON) 14 under a nitrogen atmosphere with time duration of 12 h at room temperature. Replacing the anion counterpart, Mn(salen)Br **(A2)** also produced the same result. Other Mn(salen) complexes were found to give inferior results in comparison to either **A1** or **A2** (see Supporting Information). Variation of the amount of sodium hypochlorite (NaOCl) showed that 4 mL of NaOCl (0.6 M) is optimal for this reaction, and lower concentration of NaOCl retarded the reactivity of this reaction. We also found that dilution with solvent CH_2Cl_2 had an adverse effect on this reaction (Table 1). The reaction mixtures were monitored by GC-MS and yields were determined by GC with respect to the substrate. Control reaction in absence of the Mn(salen) catalyst did not produce any desired product.

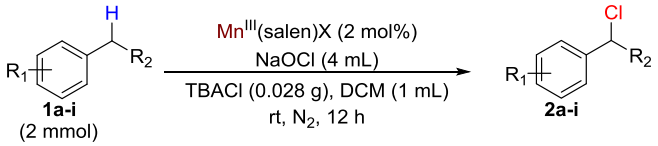
With optimized reaction conditions, we examined the scope of this methodology (Scheme 2). For toluene (**1b**) we got benzyl chloride (**2b**) with TON 10. Interestingly, we did not observe any chlorination on the aromatic ring. In the presence of a halide substituent (**1c**), the reaction proceeded smoothly to give benzylic chlorinated product (**2c**). The biphenyl system (**1d**) under the present reaction conditions afforded the respective product (**2d**) with a relatively high TON 16. Even the biphenyl system containing electron withdrawing group such as cyano group (**1e**) was tolerated to give corresponding benzylic chlorinated product (**2e**). Naphthalene system (**1f**) also worked well to give the expected chlorinated product (**2f**). Diphenylmethane and isobutyl benzene were chlorinated at benzylic site (**2g** and **2h**) along with formation of some dimerized products. In case of α-tetralone, along with benzylic chlorinated product (**2i**) some amount of α,β-unsaturated ketone (**2i'**) was formed in the ratio 2.5:1.

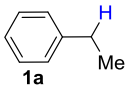
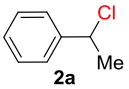
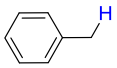
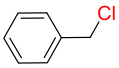
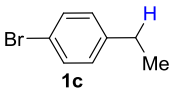
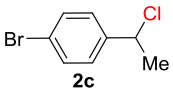
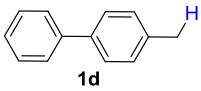
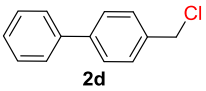
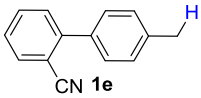
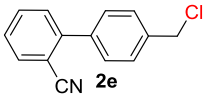
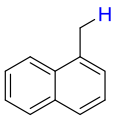
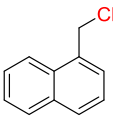
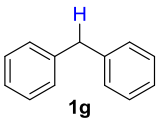
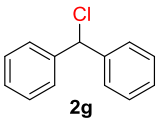
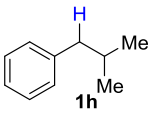
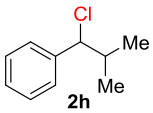
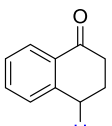
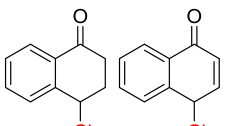
To demonstrate the synthetic potential of our method, we applied Mn(salen) chlorination method to a bioactive molecule (protected analogue). Ibuprofen methyl ester **3**, a nonsteroidal anti-inflammatory drug, when subjected to this method afforded a regioselective benzylic chlorinated product **4** with 40% isolated yield (Scheme 3).

Mn-salen catalyst (**A2**) was characterized by X-ray crystallography (Figure 2) and ESI-MS ($m/z = 599.3$). Mn(salen)X complex (**A1/A2**) gave an orange-brown colored solution in CH_2Cl_2 which showed an absorbance band in UV-Vis spectroscopy at λ_{max}, 440 nm, ($\varepsilon_{max} \sim 6.4 \times 10^3 M^{-1}\ cm^{-1}$) along with another weak band at λ_{max}, 510 nm (Supporting Information).[20]

The orange-brown color of the solution of complex **A1/A2** turned to green color upon addition of an excess of oxidant aqueous NaOCl solution. UV-Vis spectrum of this solution showed a new broad absorption band around λ_{max}, 640 nm, which indicates the formation of high-valent Mn(V)-oxo species (Figure 3).[20,21]

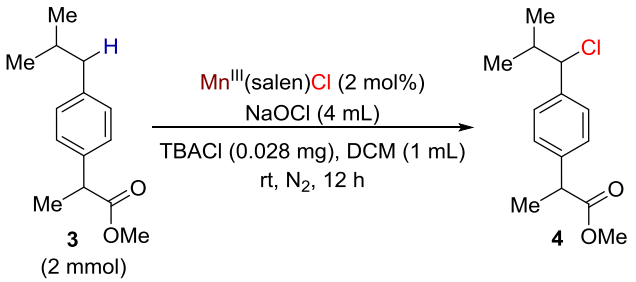
Further, time-dependent UV-Vis spectra showed a gradual decrease of this band at 640 nm upon reaction with ethylbenzene at room temperature (Figure 4). Finally, the color of the solution changes from green to brown indicating the regeneration of the starting complex $[Mn(salen)]^+$. A kinetic analysis of disappearance of Mn-oxo species during oxidation of ethylbenzene revealed a pseudo-first order rate dependency with rate constant $k_1 = 4.9 \times 10^{-2}\ s^{-1}$.



Entry	Substrate	Product	Yield (%)	TON
1	 1a	 2a	28[a]	14
2	 1b	 2b	20[b]	10
3	 1c	 2c	12[b]	6
4	 1d	 2d	32[b]	16
5	 CN 1e	 CN 2e	20[b]	10
6	 1f	 2f	20[b]	10
7	 1g	 2g	10[b],[c]	5
8	 1h	 2h	38[a],[c]	19
9	 1i	 (2i : 2i')	60[a]	30 (2.5 : 1)

Scheme 2. Substrate scope for benzylic chlorination. TON for catalyst was calculated as the mol of product formed per mol of catalyst used. [a] yield of the product was determined by GC. [b] yield of the product was determined from isolated product. [c] 5–6% of dimerized product was formed.

Further, we conducted ESI-MS study to identify the intermediates.[22] We have recorded the mass spectrum of the $[Mn^{V}(salen)(O)]^{+}$ prepared from a $[Mn^{III}(salen)]^{+}$ solution in CH_2Cl_2 upon addition of excess aqueous NaOCl. We have detected both $[Mn^{V}(salen)(O)]^{+}$ (m/z = 615.31) and $[Mn^{IV}(salen)(OH)]^{+}$(m/z = 616.33) (formed due to the hydrogen atom abstraction of $Mn^{V} = O$ from CH_2Cl_2). Interestingly both the *experimentally* obtained spectra matched well with the *simulated* spectra (Figure 5).



Scheme 3. Selective benzylic chlorination of ibuprofen methyl ester. Chlorination to oxidation product ratio is 4:1.

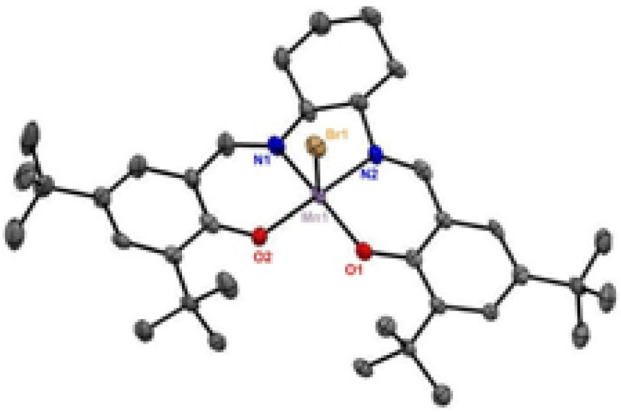


Figure 2. ORTEP diagram of [Mn(salen)Br]. Mn has square pyramidal geometry.

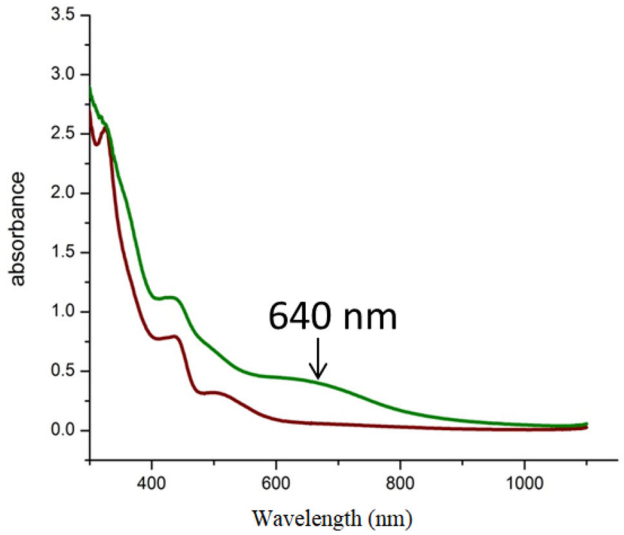


Figure 3. UV-Vis spectral changes upon addition of excess NaOCl into CH_2Cl_2 solution of Mn(salen)X (green line). UV-Vis spectrum of Mn(salen)X in CH_2Cl_2 (red line).

We choose EPR spectroscopy for the detection of Mn^{IV}(salen) species as Mn(IV) is a paramagnetic system (d^3 electronic configuration) and shows well-characterized EPR signals, whereas Mn^{V} and Mn^{III}

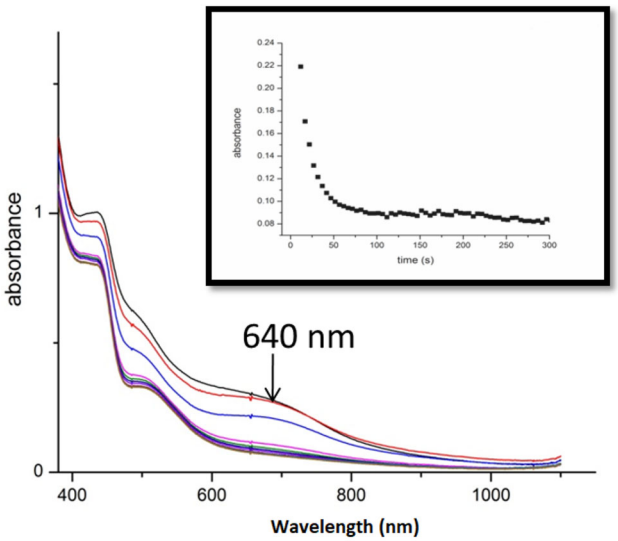


Figure 4. UV-Vis spectral changes during oxidation of ethylbenzene. Inset: Decay of absorption at 640 nm.

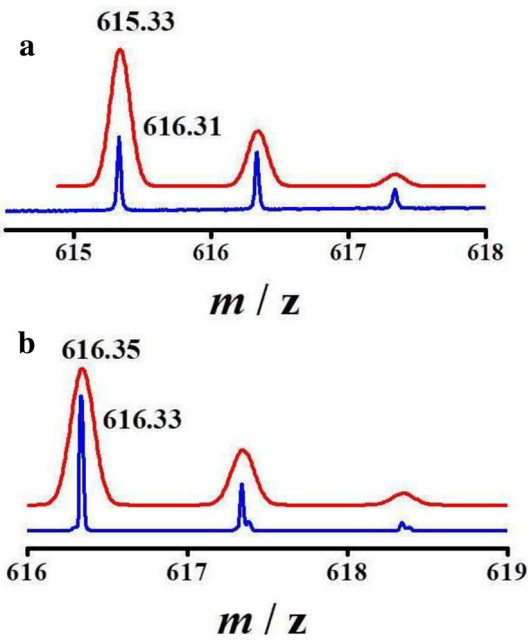


Figure 5. (a) ESI-MS spectrum of $[Mn^{V}(salen)(O)]^{+}$; (b) ESI-MS spectrum of $[Mn^{IV}(salen)(OH)]^{+}$(experimental (blue) and simulated (red)).

complexes are EPR-silent at the usual X-band frequencies.[22] For the EPR study, a 10 mM solution of Mn^{III}(salen) in CH_2Cl_2 was prepared, subsequently, 5 equiv. of PhIO was added which generated green color of Mn^{V}=O species. Then 10 equiv. of ethylbenzene was added to this solution (*noteworthy, the resulting solution provided C–H oxidation product of ethylbenzene, 1-phenylethanol and acetophenone via HAA step*). This solution displays an EPR spectrum with *g* values

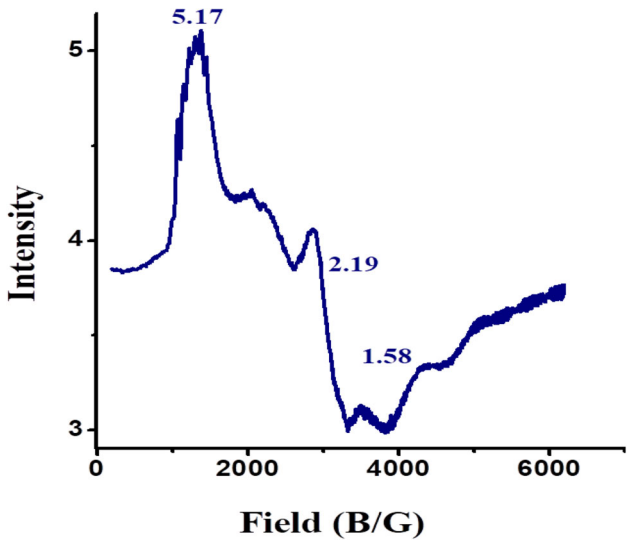


Figure 6. X-band EPR spectra of the Mn^{IV}(salen) complexes in CH_2Cl_2 at 100 K (frequency 9.5 GHz) generated from the Mn^{III}(salen) Cl complex **A1** + PhIO (5 equiv.) + ethylbenzene (10 equiv.).

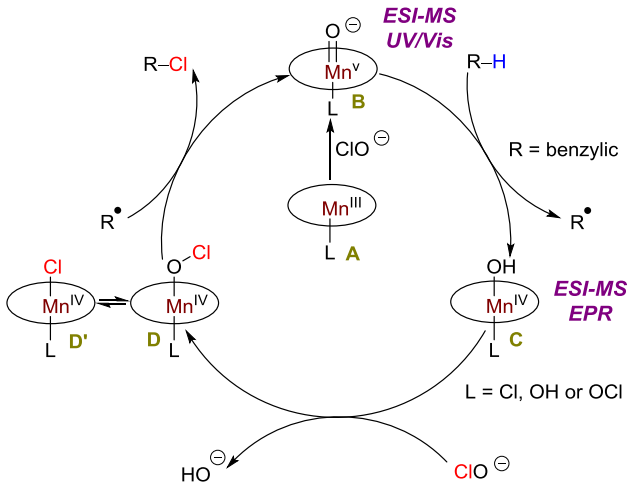


Figure 7. Proposed mechanistic cycle.

of 5.17, 2.19 and 1.58 implicating the formation of a Mn^{IV} intermediate during manganese salen-catalyzed benzylic chlorination. These g values are characteristic of a d^3 Mn^{IV}-system with $S = 3/2$ which arise from the $ms = \pm 1/2$ with rhombic symmetry.[21,23] The signal at $g = 5.17$ also displays six-line hyperfine splitting as expected for $I = 5/2$ of ^{55}Mn nucleus (Figure 6).

In the absence of ethylbenzene, we got similar EPR signals under the same experimental condition. This can be addressed by the proton abstraction of Mn^{V}=O species (generated upon addition of PhIO to Mn^{III}(salen)Cl in CH_2Cl_2) from solvent CH_2Cl_2.

Based on our initial mechanistic studies and literature reports,[24] we propose a catalytic cycle for the chlorination (Figure 7). The Mn-catalyst (**A**) is first oxidized by basic NaOCl to form Mn^{V}=O (**B**) complex (supported by ESI-MS and UV/Vis), which then abstracts hydrogen from substrate generating free benzyl radical and Mn^{IV}–OH (**C**) complex (supported by ESI-MS and EPR). For a few substrates (isobutylbenzene, diphenylmethane), the formation of dimerized products indicates the formation of a stable benzyl radical. Then Mn^{IV}–OCl (**D**) is being generated from Mn^{IV}–OH by ligand exchange with NaOCl. In the next step, benzyl radical abstracts chlorine from Mn^{IV}–OCl to form chlorinated product and regenerate Mn^{V}=O complex.

4. Conclusions

In summary, we report a method for benzylic C–H chlorination catalyzed by easily synthesizable and tunable Mn-(salen) complex where cheap NaOCl has been used as the chlorinating agent. Here, we are proposing that the reaction is passing through an Mn(V)=O species which can abstract a hydrogen atom from substrate generating benzylic radical. The formation of high-valent manganese species is supported by ESI-MS and UV-Vis studies. A further development of this methodology can accomplish late-stage derivatization of various bioactive molecules containing benzylic site.

Supplementary Information (SI)

All additional information, ^1H NMR, ^{13}C NMR, Mass and GC-MS spectral data for the characterization of compounds are given in the Supporting Information. Supplementary Information is available at www.ias.ac.in/chemsci.

Acknowledgements

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