# Iron(III) porphyrin-catalysed oxidation reactions by *m*-chloro-perbenzoic acid: Nature of reactive intermediates

A AGARWALA, V BAGCHI and D BANDYOPADHYAY*

Department of Chemistry, Indian Institute of Technology, New Delhi 110 016, India
e-mail: dkbp@chemistry.iitd.ac.in

**Abstract.**   The reaction of *m*-chloroperbenzoic (*m*-CPBA) acid with meso-*tetrakis* (pentafluorophenyl) porphynatoiron(III) chloride ($F_{20}$TPPFe(III)Cl ) has been studied in dichloromethane and acetonitrile medium at $25 \pm 1°C$. The reactive intermediates formed in this reaction have been quantitatively trapped by 2,4,6-tri *t*-butylphenol (TTBP) in both the solvents. It has been observed that the kinetic plots of the formation of TTBP• radical in dichloromethane are all multiexponential, supporting the formation of more than one reactive intermediate in this solvent. In acetonitrile solvent the formation of TTBP• radical was however observed to be distinctly single exponential. Different kinds of reactive intermediates are proposed in these two solvents.

**Keywords.**   Tri *t*-butylphenol; catalysed oxidation; *m*-chloroperbenzoic acid.

## 1.   Introduction

Iron(III) porphyrin-catalysed oxidation reactions of various organic substrates by terminal oxidants such as iodosylarenes, peracids, hydroperoxides have been studied extensively in the last few decades.[1–4] Initially, it was proposed that iodosylarenes react with Iron(III) porphyrin catalyst to evolve oxoiron(IV) cation radical exclusively. There was ambiguity regarding the nature of the intermediate structure where the terminal oxidant was either a peracid or a hydroperoxide. The involvement of only the oxoiron(IV) cation radical was proposed in some studies, however, oxoiron(IV) porphyrin species was also proposed where the terminal oxidant was hydroperoxide in particular.[5–8] Recent studies however indicated the presence of multiple reactive intermediate in such oxidising systems.[9–12] In the closely related enzyme (cytochrome P-450)-catalysed similar reactions, involvement of multiple reactive intermediates is also proposed.[13–15] Most of the model compound catalyzed oxidation reactions are studied in mixed solvents. In our present study we have chosen *m*-chloroperbenzoic acid (*m*-CPBA) as the terminal oxidant and meso-*tetrakis* (pentafluorophenyl) porphynatoiron(III) chloride, $F_{20}$TPPFe(III)Cl as the catalyst and we have chosen 2,4,6-tri-*t*-butylphenol as the highly reactive substrate to address the issue of the reactive intermediate structure in this oxidising system. Our results have clearly indicated that the nature of the reactive intermediate is highly dependent on the solvent system.

## 2.   Experimental

### 2.1   *General conditions*

Dichloromethane and acetonitrile were dried over $CaCl_2$ and were freshly distilled from $P_4O_{10}$. TTBP, *m*-CPBA and $F_{20}$TPPFe(III)Cl were purchased from Aldrich. TTBP was recrystallised four times from ethanol–water (95 : 5), dried in air and then over $CaCl_2$. *m*-CPBA was purified by the procedure described elsewhere.[16] UV–visible spectral measurements were taken with a Perkin–Elmer Lambda (2S) spectrometer. The cell holder of the spectrometer was connected to a Julabo F-30 temperature regulator and kinetic data were collected at $25 \pm 1°C$. The active oxygen concentration of *m*-CPBA was determined iodometrically: Accurately weighed 50–55 mg of solid *m*-CPBA, 1 ml chloroform, 1 g of $NaHCO_3$, 2 g of potassium iodide were taken into an Erlenmeyer flask containing 50 ml of water. Glacial acetic acid (5 ml) was added to the mixture. The flask was quickly stoppered and was kept in dark for 15 min. The liberated iodine was titrated with standardized thiosulphate solution using starch as indicator. The 1 ml of 0·1N thiosulphate was taken to be equivalent to 0·00863 g of pure *m*-CPBA.

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**Table 1.** $F_{20}$TPPFe(III)Cl-catalysed oxidation of TTBP by *m*-CPBA in dichloromethane at $25 \pm 1°C$.

| TTBP (mM) | *m*-CPBA (mM) | Catalyst ($i$M) | Cat : Oxd | Yield[a] (%) | Time of highest yield (min) | $t_{1/2}$ (s) | Yield[a] after 10 s (%) |
|---|---|---|---|---|---|---|---|
| 54·0 | 0·92 | 6·9 | 1 : 133 | 98 ± 2 | 87 | 1570 | 0·4 ± 0·1 |
| 54·0 | 0·92 | 13·1 | 1 : 70 | 98 ± 2 | 48 | 930 | 4·1 ± 0·2 |
| 54·0 | 0·92 | 26·0 | 1 : 35 | 98 ± 2 | 17 | 305 | 10·0 ± 0·1 |
| 54·0 | 0·92 | 39·0 | 1 : 24 | 98 ± 2 | 10 | 170 | 16·1 ± 0·2 |
| 54·0 | 0·23 | 57·0 | 1 : 4 | 88 ± 1 | 10 | 35 | 19·0 ± 1·0 |
| 27·0 | 0·90 | 12·7 | 1 : 71 | 91 ± 2 | 60 | 1195 | 1·5 ± 0·2 |
| 78·0 | 0·88 | 13·2 | 1 : 67 | 96 ± 2 | 36 | 420 | 4·0 ± 0·2 |
| 112 | 0·88 | 13·2 | 1 : 67 | 97 ± 2 | 30 | 380 | 4·4 ± 0·2 |
| 210 | 0·88 | 13·1 | 1 : 66 | 97 ± 2 | 30 | 330 | 5·6 ± 0·1 |
| 500 | 0·88 | 13·1 | 1 : 66 | 82 ± 3 | 21 | 230 | 8·0 ± 0·3 |

[a]Yield was calculated with respect to total *m*-CPBA concentration
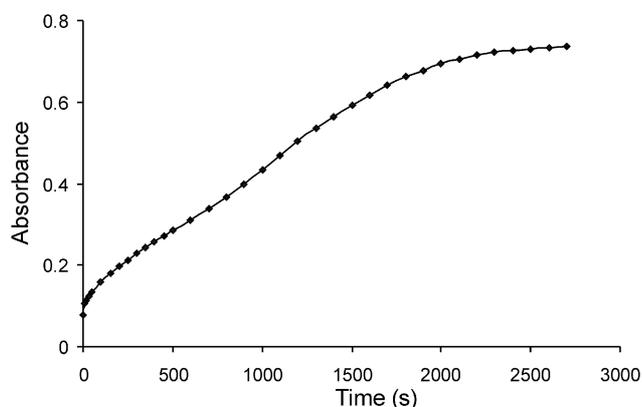


**Figure 1.** Absorbance vs time plot of 2,4,6-tri *t*-butyl-phenoxy radical formation in dichloromethane. TTBP = 54 mM; *m*-MCPBA = 0·92 mM; $F_{20}$TPPFe(III)Cl = 13·1 $i$M.

### 2.2 *Kinetic experiments*

In a typical kinetic experiment, TTBP (21 mg, 0·08 mM) was taken in a cuvette fitted with silicon rubber septa. The cuvette was degassed by blowing argon over it for 15 min. Dichloromethane was taken in a 5 ml gas-tight syringe and was degassed by bubbling argon through the solvent for 15 min. This degassed dichloromethane (1·5 ml) was used to dissolve the TTBP in the cuvette. A standard solution of $F_{20}$TPPFe(III)Cl in dichloromethane was added to the cuvette so that the final catalyst concentration was in the required range given in table 1. The *m*-CPBA solution was prepared in degassed dichloromethane (5·1 mg, 200 $i$l) in a small (1·5 ml) screw-capped vial. An aliquot volume (10 $i$l) of this stock solution was added to the cell to initiate the oxidation reaction. The cell was shaken vigorously and was placed immediately in a thermostated cell holder in

a spectrophotometer and the absorbance data at 630 nm were collected at 10-second intervals. Similar experiments were conducted in acetonitrile solvent as well. The kinetic data were processed as described elsewhere.[17]

## 3. Results and discussion

In argon-saturated dichloromethane solvent, 2,4,6-tri *t*-butylphenol was reacted with *m*-CPBA alone for 6 h. We did not observe any detectable radical formation by UV–visible spectrometer.[18] When this reaction was carried out in presence of $F_{20}$TPPFe(III)Cl the yield of the radical was found to be dependent on substrate (TTBP) concentration. This reaction has been thoroughly investigated by systematic variation of the catalyst and substrate concentration. Our first objective was to account for the total terminal oxidant in terms of the 2,4,6-tri *t*-butylphenoxy radical (TTBP•) formation. We have achieved this and the selected results are presented in table 1. One representative kinetic plot of absorbance increase due to the formation of TTBP• radical vs time is given in figure 1.

It has been observed that a minimum concentration of 52 ± 2 mM of TTBP is required to trap all the reactive intermediates in these reactions when dichloromethane is the solvent. The notable feature in this study is that none of the kinetic traces are exponential. A representative plot is given in figure 1 and the quantitative spectrum of TTBP• radical in dichloromethane is given in figure 2 (bold line).

In this oxidation reaction under all the conditions, non-exponential kinetic traces were always observed. The notable feature is that within the first 10 s or so there is a fast component, which increases sys-

tematically as the ratio of the catalyst : oxidant is lowered from 1 : 133 to 1 : 4 (table 1). The total time required for the complete consumption of the reactive intermediate in terms of the TTBP• radical formation also reduces substantially when catalyst: oxidant ratio is reduced. Substrate concentration of 54–210 mM is found to be the most efficient in trapping all the reactive intermediates formed from the reaction mixture of ~0·9 mM of *m*-CPBA in presence of 6–40 $\mu$M of the catalyst. The time required for the completion of these reactions is dependent on the catalyst concentration as expected. At highest (about 500 mM) or lower (<50 mM) concentrations of TTBP, the yield of TTBP• radicals is not quantitative.
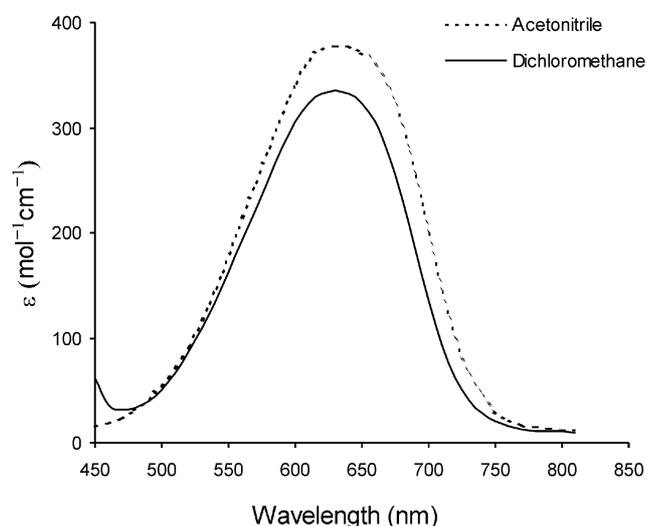


**Figure 2.** Electronic absorption spectra of TTBP• radical in two solvents.
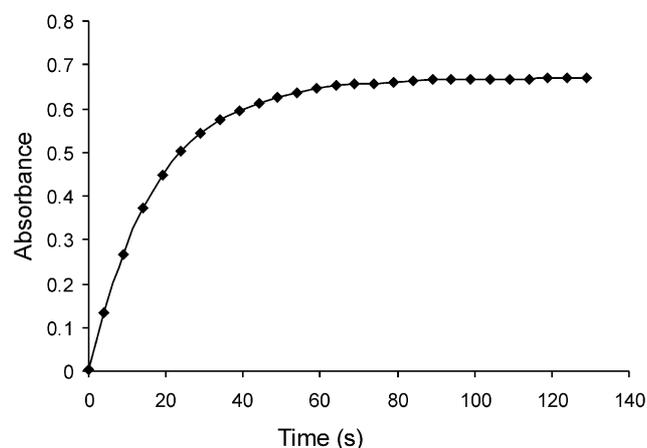


**Figure 3.** Absorbance vs time plot of 2,4,6-tri *t*-butyl-phenoxy radical formation in acetonitrile. TTBP = 50 mM; *m*-CPBA = 0·88 mM; $F_{20}$TPPFe(III)Cl = 0·95 *i*M.

The same reactions were then conducted in argon-saturated dry acetonitrile solvent. The oxidation of TTBP to TTBP• radical was observed to be very fast in this medium under the reaction conditions used to study the reaction in dichloromethane solvent. However, a judicious choice of the lower range of catalyst concentration has enabled us to depict decent kinetic traces for finer analysis of the data sets in this medium. Selected results only of the oxidation of TTBP that are closest to 100%, are summarised in table 2. A representative kinetic trace is given in figure 3. The quantitative spectrum of 2,4,6-tri *t*-butylphenoxy radical in acetonitrile is given in figure 2 (dotted line). A comparison of figures 1 and 3 clearly indicates that exponential behaviour is not seen in dichloromethane, but is distinct in acetonitrile.

The rate of reaction in acetonitrile is a few orders of magnitude higher than that has been observed in dichloromethane solvent. The plot of –Ln ($A_a$–$A_t$) vs time ($A_a$ = highest absorbance observed at the end of the reaction and $A_t$ = absorbance at real time) is given in figure 4 corresponding to the data set presented in figure 3. The slopes of such plots give the $k_{obs}$ values, which are given in table 2.

We believe that in dichloromethane solvent, the catalyst–oxidant adduct is formed first, which then decomposes mainly homolytically to evolve oxoiron(IV) species. Thus, in this medium, both the catalyst–oxidant adduct, $C_6H_4ClCOO•$ radical and oxoiron(IV) are the major reactive intermediates. The formation of oxoiron(IV) porphyrin cation radical by the heterolytic cleavage is expected to be at a
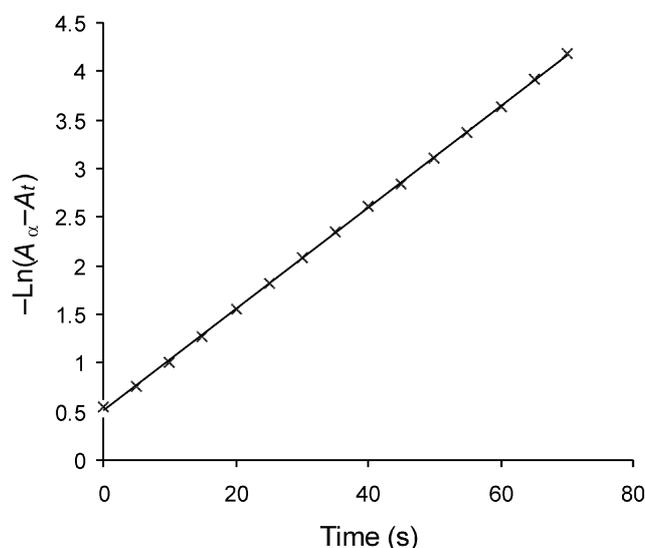


**Figure 4.** Plot of –Ln($A_a$–$A_t$) vs time.

**Table 2.** $F_{20}$TPPFe(III)Cl-catalysed oxidation of TTBP by *m*-CPBA in acetonitrile at $25 \pm 1°$C.

| TTBP (mM) | Catalyst ($\mu$M) | *m*-CPBA (mM) | % Yield[b] | $k_{obs}$ (s$^{-1}$) | $k_{obs}$/[Cat.] ($\times 10^{-4}$ mol$^{-1}$ s$^{-1}$) |
|---|---|---|---|---|---|
| 6·25 | 0·95 | 0·88 | 89·8 ± 0·2 | 0·037 ± 0·001 | 3·90 ± 0·10 |
| 12·5 | 0·95 | 0·88 | 94·5 ± 0·5 | 0·033 ± 0·002 | 3·47 ± 0·21 |
| 25·0 | 0·95 | 0·88 | 96·8 ± 0·2 | 0·050 ± 0·001 | 5·26 ± 0·10 |
| 50·0 | 0·95 | 0·88 | 99·5 ± 0·5 | 0·055 ± 0·002 | 5·78 ± 0·21 |
| 125·0 | 0·95 | 0·88 | 96·5 ± 0·2 | 0·068 ± 0·001 | 7·16 ± 0·10 |
| 6·25 | 1·79 | 0·88 | 90·5 ± 0·5 | 0·067 ± 0·001 | 3·74 ± 0·06 |
| 50·0 | 0·95 | 0·44 | 99·6 ± 0·2 | 0·065 ± 0·001 | 6·84 ± 0·10 |

[b]Yield was calculated with respect to *m*-CPBA concentration
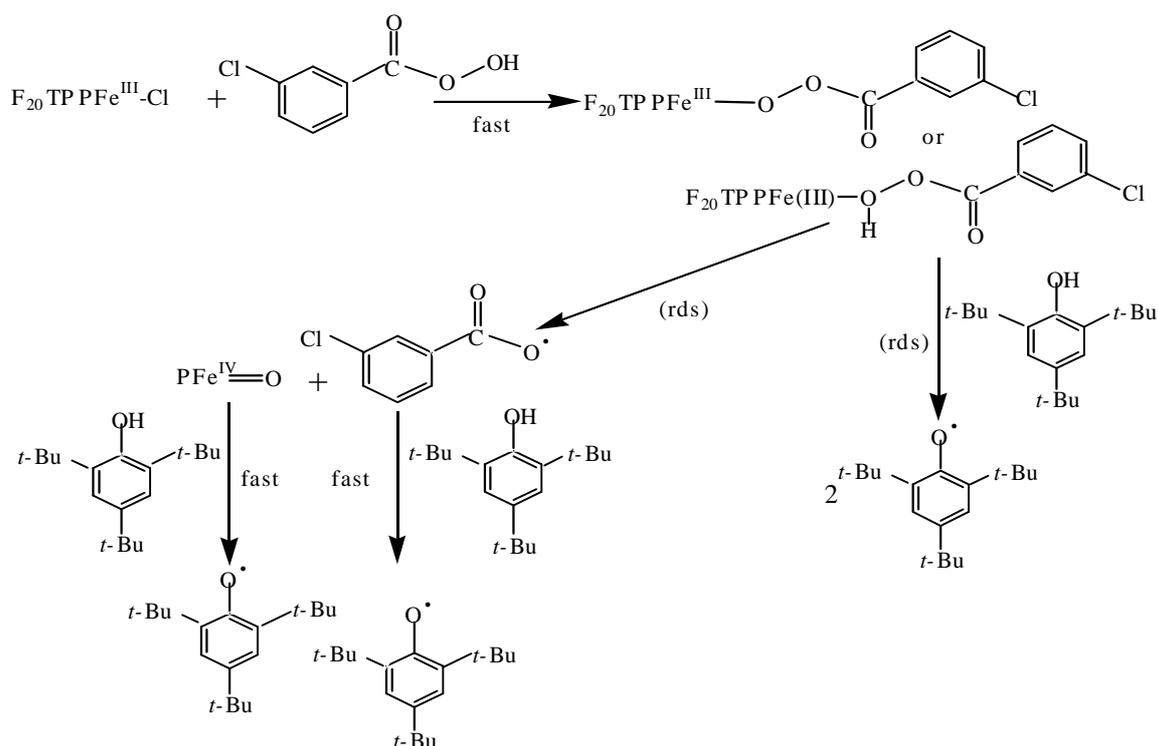


**Scheme 1.** Reactive intermediates in dichloromethane.
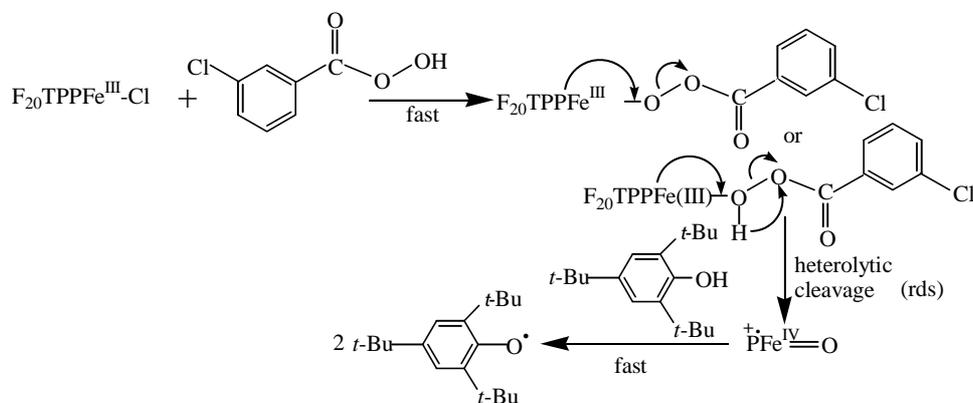


**Scheme 2.** Reactive intermediates in acetonitrile.

minimum level in this non-polar medium. The proposed route of the formation of these multiple reactive intermediates is represented in scheme 1.

Heterolytic cleavage of the peroxy bond should be expected to be mainly dominating in acetonitrile solvent because it is a more polar solvent. Thus, the involvement of the oxoiron(IV) cation radical is mainly responsible for the exponential evolution of 2,4,6-tri *t*-butylphenoxy radical in this solvent. The proposed pathway of the formation of oxoiron(IV) porphyrin radical cation in acetonitrile medium is represented in scheme 2.

This explanation supports the observed single exponential plot and also the very high rate of this 2,4,6-tri *t*-butylphenoxy radical production in a single step.

## 4. Conclusion

The present study supports conclusively the presence of multiple reactive intermediates in iron(III) porphyrin-catalysed oxidation reaction in dichloromethane medium, where *m*-CPBA is the terminal oxidant. The results also indicate the presence of only a single reactive intermediate in this reaction in acetonitrile solvent. Variation of the catalyst structure and the polarity of the solvent to detect the transition point between such variable intermediate structure in solution are under investigation.

## Acknowledgement

## References

1. McLain J, Lee J and Groves J T 2000 In *Biomimetic oxidations catalyzed by transition metal complexes* (ed.) Meunier B (London: Imperial College Press) pp 91–169
2. Meunier B 1992 *Chem. Rev.* **92** 1411
3. Dolphin D and Traylor T G 1997 *Acc. Chem. Res.* **30** 251
4. Sheldon R A 1994 *Metalloporphyrins in catalytic oxidations* (New York: Marcel Dekker)
5. Grinstaff M W, Hill M G, Labinger J A and Gray H B 1994 *Science* **264** 1211
6. Traylor T G, Kim C, Richards J L, Xu F and Perrin C L 1995 *J. Am. Chem. Soc.* **117** 3486
7. Bruice T C 1991 *Acc. Chem. Res.* **24** 243
8. Groves J T, Gross Z and Stern M K 1994 *Inorg. Chem.* **33** 5065
9. Collmann J P, Chien A S, Eberspacher T A and Brauman J I 2000 *J. Am. Chem. Soc.* **122** 11098
10. Collman J P, Zeng L and Decreau R A 2003 *Chem. Commun.* **24** 2974
11. Suzuki N, Higuchi T and Nagano T 2002 *J. Am. Chem. Soc.* **124** 9622
12. Nam W, Park S E, Lim I K, Lim M H, Hong J and Kim J 2003 *J. Am. Chem. Soc.* **125** 14674
13. Chandrasena R E P, Vatsis K P, Coon M J, Hollenberg P F and Newcomb M 2004 *J. Am. Chem. Soc.* **126** 115
14. Jin S, Makris T M, Bryson T A, Sligar S G and Dawson J H 2003 *J. Am. Chem. Soc.* **125** 3406
15. Vaz A D N, McGinnity D F and Coon M J 1998 *Proc. Natl. Acad. Sci. USA* **95** 3555
16. Traylor T G, Lee W A and Stynes D V 1984 *J. Am. Chem. Soc.* **106** 755
17. Kamaraj K and Bandyopadhyay D 1999 *Organometallics* **18** 438
18. TTBP$^\bullet$ radical absorbs strongly at 630 nm ($\mathring{a} = 335$ mol$^{-1}$ cm$^{-1}$).