

Cytochrome P-450 model reactions: a kinetic study of epoxidation of alkenes by iron phthalocyanine

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Abstract

A kinetic study for measuring the relative rate of the catalytic epoxidation of various alkenes has been employed based upon the disappearance of the 1,4-diphenylbutadiene. Iron(III) phthalocyanine chloride as catalyst, imidazole as cocatalyst, iodossylbenzene as oxygen donor and a mixture of dichloromethane, methanol, water (80:18:2) as solvent, were used for achieving to a homogeneous system. Effects of nitrogen donor bases such as pyridine, piperidine and collidine on the yield of alkenes epoxidation were investigated and possibility of the same mechanism for iron phthalocyanine and porphyrin has been demonstrated. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Iron phthalocyanine; Alkene epoxidation; Kinetic; Relative rate

1. Introduction

The epoxidation of alkenes catalyzed by transition metals is a field, which extensively has been developed during last two-decades [1,2]. Among them, metalloporphyrins in oxidation of substrates with various single-oxygen atom donors have had a major role for understanding of biological related reaction of cytochrome P-450, where oxo-metalloporphyrins are accepted as reactive intermediate [3–6]. Phthalocyanine with a similar structure to the porphyrin has intensively been investigated in numbers of areas such as industrial colorants and electrophotography, photoconductors, nonlinear optic, optical data storage, photodynamic therapy of cancer, fuel cell, chemical sensor, etc. [7–10]. Moreover, Larsen and Jorgensen [11] have reported that manganese and iron phthalocyanines are among the most effective

metallophthalocyanines for alkenes epoxidation when iodossylbenzene were employed as the oxygen donor. Banfi et al. [12] have compared reactivity of Mn-octanitrophthalocyanine with different Mn-porphyrins where peracetic acid was oxygen donor and concluded that Mn-phthalocyanine have comparative catalytic activity to tetra phenyl porphyrin iron(III) chloride. Nappa and Tolman [13] have reported that perfluorinated FePc catalyzed the oxidation of cyclohexane by iodossylbenzene and Ellis and Lyons [14] have shown that the N_3^- ligand has promotional effect on catalytic hydroxylation of alkanes by metallophthalocyanines. Hadasch and Meunier [15] have recently reported that water soluble iron tetrasulfophthalocyanine is effective catalyst for oxidation of aromatic compounds.

In spite of similarity between metallophthalocyanines and metalloporphyrins, the latter has played an important role in understanding the mechanism of oxidation catalyzed by cytochrome P-450 [3], however, metallophthalocyanines have not been

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studied to the same extent in the mechanistic view as catalyst in the oxidation reactions [10]. To this end, in present work we used PcFeCl as a homogeneous catalyst and iodossylbenzene as oxygen donor to study epoxidation of alkenes. Possibility of the same reaction pathway and the mechanism of metalloporphyrins and metallophthalocyanines through a kinetic method were investigated.

2. Experimental

2.1. Materials

Phthalocyanine iron(III) chloride were obtained from Mide Century Co. Iodossylbenzene was synthesized according to literature method [16]. 1,4-Diphenylbutadiene (DPBD) 98% purchased from Aldrich Chemical Co. and imidazole from Riedel–Dehean. Most of the alkenes were the best grade available from Merck Chemical Co. and were used as received. Solvent for all of these studies was a mixture of methylene chloride, methanol (Merck, spectra grade), and distilled water in respective ratio of 80:18:2 vol.%

2.2. Instrument

The UV–VIS spectra and kinetic measurement have done by a Shimadzu 2100 spectrophotometer. Product analyses has done by a Shimadzu GC 8A gas chromatograph equipped with an OV-17 10% 2 M column. Gas chromatography–mass spectroscopy (GC–MS) was performed with a Varian 3400 spectrometer.

2.3. Kinetic method

Catalytic solutions containing, PcFeCl 10^{-4} M (with imidazole 5×10^{-4} M), 1,4 diphenylbutadiene 10^{-4} M (DPBD), and iodossylbenzene 10^{-3} M in the standard solvent (80:18:2 CH₂Cl₂, CH₃OH, H₂O) were prepared. A sufficient amount of oxidant was added to the solution of catalyst and diphenylbutadiene in a cell (1 cm path) to bring concentration of oxidant to 5×10^{-4} M, catalyst to 1×10^{-5} M and DPBD to 5×10^{-5} M. The decrease in absorbance of the DPBD at 348 nm ($\epsilon = 3.7 \times 10^4$) versus time at 25°C was followed immediately. Absorbance versus time curve indicates a pseudo-first-order reaction (Fig. 1).

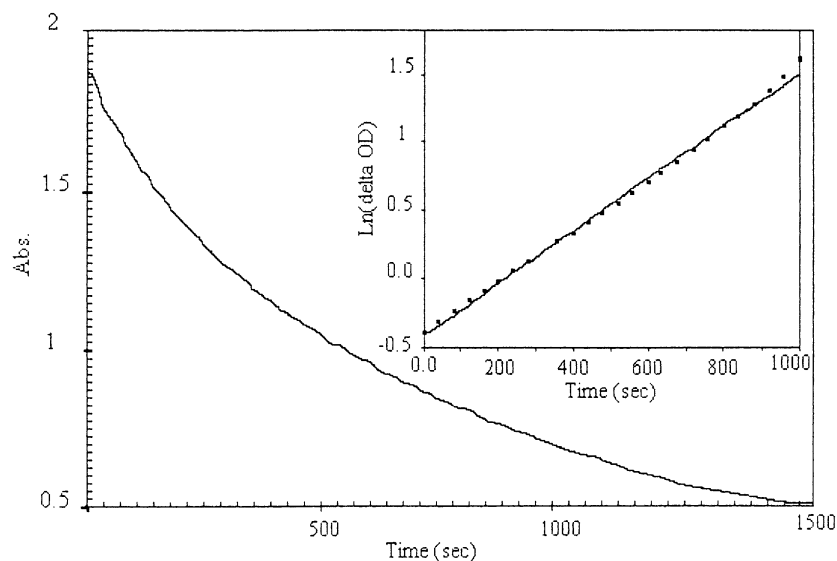


Fig. 1. Plot of absorbance vs. time and $\ln(\Delta OD)$ vs. time at $\lambda = 348$ nm after addition of iodossylbenzene (c_1) to the solution of phthalocyanine iron chloride (c_2), 1,4-diphenylbutadiene (c_3) at 5×10^{-5} M imidazole. Concentrations: $[c_1] = 5 \times 10^{-4}$ M, $[c_2] = 1 \times 10^{-5}$ M and $[c_3] = 5 \times 10^{-5}$ M.

2.4. Relative rates

The relative rates of alkenes reactions were determined by competition method. In this procedure, DPBD was used as a reference substrate and decreases in its absorbance at 348 nm was monitored versus time with and without the second alkenes. This experiment was repeated in four different concentrations of each alkene and the k_{rel} , averaged. After the addition of a second alkene to the mixture of catalyst, DPBD and oxidant, the rate of consumption of DPBD were decreased, while the obtained first-order rate constant like metalloporphyrins was independent of the second alkene as expected (Fig. 3) [17]. Quantitative conversion of DPBD to monoepoxide was confirmed by NMR [17]. Product of cyclooctene oxidation was analyzed by GC and GC–MS and shown the formation of cyclooctene oxide as main product. It must be noted that the catalyst has some absorbance at 348 nm and by addition of the oxidant, absorbance of catalyst at this λ has changed during first 30 s until the solution became colorless, then after this time, all changes in the absorbance at 348 nm was due to the DPBD. All of the kinetic studies were performed after this 30 s initial delay.

2.5. Effect of bases

Heterocycle bases such as pyridine or imidazole were found to increase the initial rate of epoxidation of alkenes. Competition rate in the presence of imidazole, pyridine, collidine and piperidine were determined by GC. In these experiments, 0.077 g (0.35 mmol) iodosylbenzene was added to a mixture of 1.8×10^{-3} M FePcCl and 1.53 M cyclooctene in the 5 ml of standard solvent during 30 min. The yield of cyclooctene oxide (relative to the oxidant) was determined by GC after 5 h of reaction time. In another series of experiments, the yield of cyclooctene oxide formation was determined in the presence of 5–100-folds excess concentration of nitrogenous bases relative to the catalyst, see Table 2.

3. Results and discussion

The kinetic study was based on competitive method established by Traylor for alkene epoxidation with

iron porphyrins [17]. To reach homogeneous system, due to insolubility of iron phthalocyanine, the addition of pyridine, collidine, piperidine and imidazole to the catalyst was tested. All caused the solubility of the catalyst increase, while they played a base catalytic role and were oxidized partially in our system. Among these, imidazole had the advantage of not being oxidized considerably and does not affect kinetics of the oxidation of DPBD in the range of 5–10-folds excess to the catalyst. Therefore, we have chosen imidazole as cocatalyst in five-folds excess to the catalyst.

Iodosylbenzene was employed as oxidant in epoxidation with PcFeCl which had no reaction with DPBD in the absence of catalyst. The rate of oxidant decomposition could be ignored in the presence of catalyst in our reaction conditions. With 10-folds excess of *meta*-chloroperbenzoic acid, as an oxidant, epoxidation reaction with DPBD stops in the half way in our system. It seems, peracids are not among the best oxygen donors where phthalocyanines are

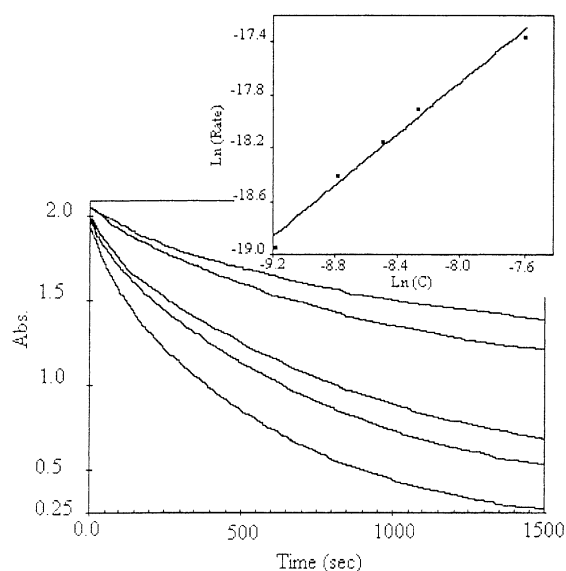


Fig. 2. Plot of absorbance vs. time and $\ln(\text{rate})$ vs. $\ln[c]$ at 348 nm after addition of iodosylbenzene to a solution of phthalocyanine iron chloride ($c = 1 \times 10^{-5}$ M), 1,4-diphenylbutadiene ($c = 5 \times 10^{-5}$ M) at 5×10^{-5} M imidazole, where oxidant concentrations was $[c_1] = 1.53 \times 10^{-5}$ M, $[c_2] = 2 \times 10^{-5}$ M, $[c_3] = 2.5 \times 10^{-5}$ M, $[c_4] = 5.1 \times 10^{-5}$ M, $[c_5] = 10.2 \times 10^{-5}$ M, respectively.

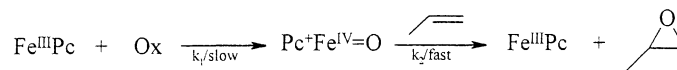
employed as catalyst [12,18,19], while the reaction with the same concentration of iodossylbenzene would be complete. Iodossylbenzene dissolved easily in our solvent system, (dichloromethane, methanol and water in the ratio of 80:18:2). DPBD was converted to monoepoxide quantitatively by our catalytic system and because consumption of alkene and oxidant are 1:1, so, we followed the changing of alkene concentration instead of oxidant.

Fig. 1 shows plot of absorbance versus time and $\ln(A - A_\infty)$ versus time after addition of

iodossylbenzene to the solution of DPBD, PcFeCl and imidazole. Consumption of DPBD was monitored by disappearance of absorbance at 348 nm. From slope of the plot B in plot 1, the rate constant for pseudo-first-order reaction, $k_{\text{obs}} = 2.2 \times 10^{-3} \text{ s}^{-1}$, and second-order rate constant,

$k = 1.9 \times 10^2 \text{ M}^{-1} \text{ s}^{-1}$, are obtained. In Fig. 2, plot of ΔOD versus time and $\ln(\text{rate})$ versus $\ln(\text{oxidant})$ has been shown. From this plot, reaction order respect to oxidant is 0.97 and is consistent with the pseudo-first-order reaction obtained in Fig. 1.

The reaction was first-order in oxidant over wide range of concentrations which have been employed (10^{-5} to 10^{-2} M). It is almost first-order in the catalyst and essentially independent of concentration or structure of the alkenes used. Then overall reaction scheme and rate law is



$$\text{Rate} = k_1[\text{cat}][\text{Ox}] = k_{\text{obs}}[\text{Ox}]$$

So, k_1 and k_{obs} can be calculated directly but not k_2 . The relative rates of reaction of an alkene and reference alkene, 1,4-diphenylbutadiene, can be obtained from Traylor's method [17] used for porphyrins due to similarity of the rate laws in these two system. For Pc: phthalocyanine iron chloride, I: the oxene intermediate, S_A : DPBD as reference substrate, S_B : second

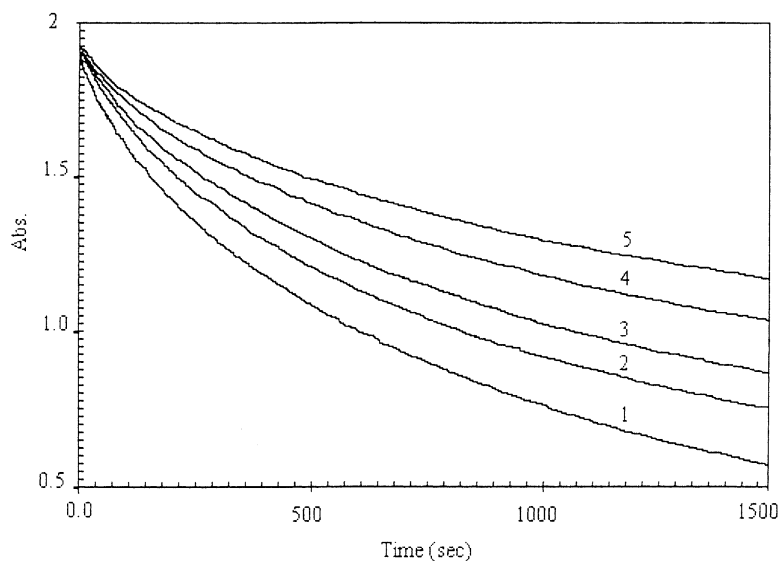


Fig. 3. Plot of absorbance vs. time at 348 nm after addition of iodossylbenzene ($c = 5 \times 10^{-4}$ M) to the solution of phthalocyanine iron chloride ($c = 1 \times 10^{-5}$ M), 1,4-diphenylbutadiene ($c = 5 \times 10^{-5}$ M) at 5×10^{-5} M imidazole and *trans*-stilbene in form that concentrations became $[c_1] = 0.0$ M, $[c_2] = 2.5 \times 10^{-4}$ M, $[c_3] = 5 \times 10^{-4}$ M, $[c_4] = 10 \times 10^{-4}$ M, $[c_5] = 15 \times 10^{-4}$ M, respectively.

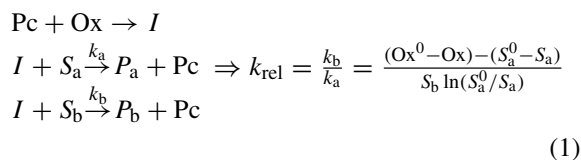
Table 1

Oxidation rates of olefins with phthalocyanine iron(III) chloride and tetrakis (2,6-dichlorophenyl) porphyrin iron(III) chloride related to DPBD at 25°C

Alkene	PcFeCl [this work]	TDCPPFeCl [17]	IP (eV)	$E_{1/2}$ (V)
DFBD	1	1	7.55	1.14
<i>Trans</i> -stilbene	$2.20 (\pm 0.01) \times 10^{-2}$	5.6×10^{-3}	8	–
Styrene	$5.7 (\pm 0.7) \times 10^{-3}$	6.9×10^{-3}	8.47	2.51
Cyclohexene	$4.7 (\pm 0.5) \times 10^{-3}$	5.2×10^{-3}	9	2.14
Cyclooctene	$4.5 (\pm 0.5) \times 10^{-3}$	1.1×10^{-2}	8.98	–
1-Hexene	$6.3 (\pm 0.9) \times 10^{-4}$	–	–	–
<i>Cis</i> -stilbene	$9.9 (\pm 0.2) \times 10^{-3}$	5.3×10^{-3}	8.2	1.53
1-Octene	$8.0 (\pm 0.9) \times 10^{-4}$	4.4×10^{-4}	9.52	2.8
Norbornene	$5.44 (\pm 0.02) \times 10^{-2}$	1.6×10^{-2}	8.81	2.02
Pyridine ^a	$1.7 (\pm 0.3) \times 10^{-1}$			
Collidine ^a	$1.1 (\pm 0.2) \times 10^{-1}$			
Piperidine ^a	$7.7 (\pm 0.3) \times 10^{-1}$			

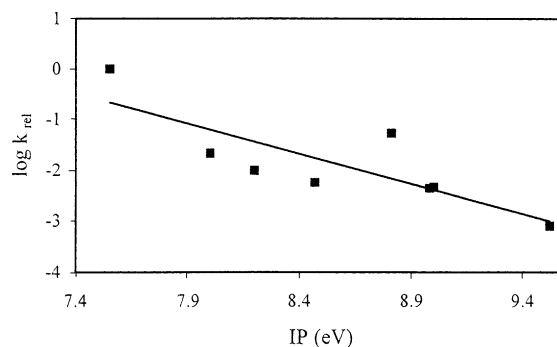
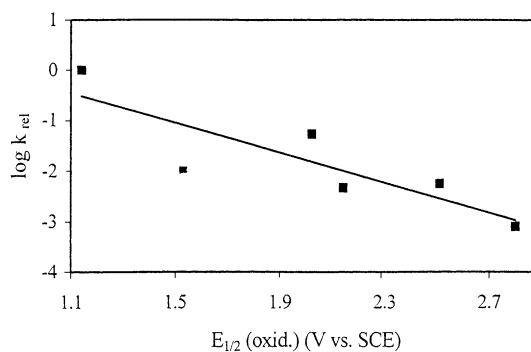
^a Calculated from GC method.

substrate and P_a and P_b are products, the reactions and the integrated form of the relative rate are



The catalytic reaction is performed once in the presence of the reference alkene, consumption of alkene is equal to oxidant consumed or oxene intermediate formed during the reaction time. In the presence of the second alkene, some of the oxene would oxidize the second alkene and the amount of the reference alkene used is decreased. So, one can use this data and Eq. (1) to calculate k_{rel} for each alkene relative to reference alkene [17]. Fig. 3 shows plot of the competitive reaction for *trans*-stilbene. For every k_{rel} , at least four different concentration of alkene are employed and the k_{rel} 's averaged. Table 1 shows the k_{rel} for some alkene in our system compared with the result obtained for porphyrin from literature. The similarity of these relative rate and its small standard deviation of k_{rel} 's added confidence to the use of our analytical method.

Plot of $\log k_{\text{rel}}$ versus gas phase ionization potential (IP) is shown in Fig. 4. We observe a reasonable linear relationship between k_{rel} and IP. A similar plot of k_{rel} against the electrode oxidation potential ($E_{1/2}$) is shown in Fig. 5, that the rate of epoxidation correlated very well with $E_{1/2}$. These correlation are good

Fig. 4. Correlation of $\log k_{\text{rel}}$ for epoxidation with ionization potentials of the alkene.Fig. 5. Correlation of $\log k_{\text{rel}}$ for epoxidation with solution oxidation potentials of the alkene.

explained by electron transfer mechanism from alkene to oxo-iron phthalocyanine intermediate which has been proposed for iron porphyrins base on similar observation [17].

Similarity between the reaction pathway, kinetic and relative rate for iron phthalocyanine and iron porphyrin may show similar mechanism for these two series of catalyst, highest rate for *trans*-styrene in PcFeCl can be explained due to planarity and less steric hindrance of PcFeCl in comparison with iron porphyrin [18].

In the presence of catalytic amounts of bases like pyridine, imidazole, collidine and piperidine not only the yield of epoxidation of cyclooctene increased but also the initial rate of epoxidation was increased. It has been reported that the yield of epoxidation will increase in the presence of such ligands due to the base catalytic property of these ligands which facilitate the O–O bond cleavage and formation of high oxo intermediate [20,21]. We also observed that the higher concentration of these bases result in competition in oxidation reaction. Table 2 shows effects of concentration of these bases to the yield of cyclooctene oxide formation. Decreases in the yield of epoxidation are due to parallel oxidation of these bases and cyclooctene.

Addition of oxidant to our system results in decoloration of phthalocyanine while the catalytic activity is preserved. Gaigneaux et al. [22] believe phthalocyanines decompose during exposure to *tert*-butyl hydroperoxide and some catalytic reactivity is due to degraded components of metallophthalocyanine. This is in contrast with having $\text{Pc}^+\text{Fe}^{\text{IV}}=\text{O}$ intermediate.

We have noticed that the addition of some reducing agent like sodium dithionite to the colorless solution

Table 2

Epoxidation yields of cyclooctene in the presence and absence of some nitrogen donor ligands catalyzed by FePcCl (1.8×10^{-3} M)

Bases	Concentration of bases relative to the catalyst (mole of base/mole of catalyst) (%)		
	5	10	100
Yield without any bases = 45%			
Imidazole (%)	55	58	— ^a
Pyridine (%)	54	57	45
Piperidine (%)	52	52.7	17
Collidine (%)	56.7	60.5	44.2

^a For concentration >10 times of the catalyst, the imidazole has interference with cyclooctene oxide.

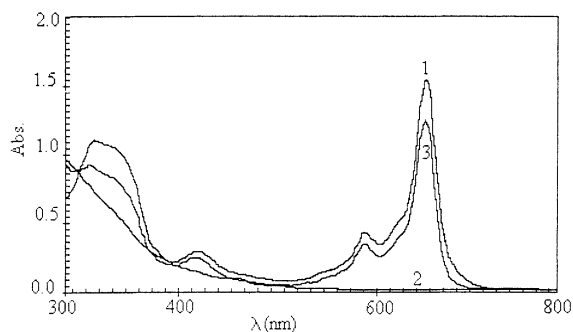
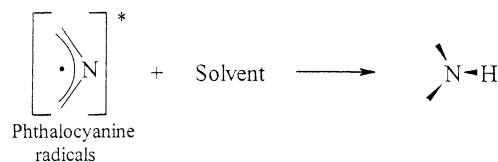
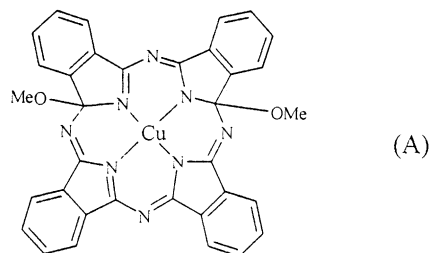


Fig. 6. UV–VIS spectrum of Fe(II)Pc (3×10^{-5} M with imidazole 1.5×10^{-4} M) trace (1), 200s after addition of iodosylbenzene (3.4×10^{-4} M), Q-band is omitted trace (2), after addition of 5×10^{-3} g sodium dithionate trace (3).

of oxidant and catalyst will restore the phthalocyanine almost quantitatively (Fig. 6). Based on the above experiment, we believe that decoloration of phthalocyanine can be due to either removing $2e$ from a_{2u} orbital of phthalocyanine and having active oxidant $[\text{Pc}^{2+}\text{Fe}^{\text{III}}=\text{O}]^+$ or production of a radical intermediate which cyclic π -system of the phthalocyanine will be disrupted by its hydrogen abstraction [23]



Product A for decoloration of the MPCs reaction with benzoyl peroxide in the presence of alcohol was proposed by Pedersen [24], but this product has characteristic absorbance between 300 and 400 nm that is not present in our system (Fig. 6).



Further studies toward nature of active oxidant in iron phthalocyanine in homogenous system are under investigation.

4. Conclusions

Combination of phthalocyanine iron(III) chloride, imidazole, iodosylbenzene, in dichloromethane, methanol, water (80:18:2) result in homogenous catalytic system. Degradation of catalyst in our system is not considerable. The reaction of oxidant with substrates was first-order in oxidant, catalyst and essentially independent of alkenes used. Consequently, kinetic study demonstrate similarity between the reaction pathway, relative rates and products (epoxide) for iron porphyrins and iron phthalocyanines.

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