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Kinetics of the autoxidation of adrenaline and [copper(II)(adrenaline)]$^{2+}$ in alkaline aqueous and micellar media

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Abstract The kinetics of autoxidation of adrenaline and [Cu(adrenaline)]$^{2+}$ complex by dissolved oxygen in alkaline aqueous and micellar media has been studied. The reaction is initiated by the removal of amino-H^+ protons of adrenaline by hydroxide ion, followed by cyclization. The values of ($1/k_{obs}$) for the autoxidation of both species were found to be linearly dependent upon 1/[OH^-]. The reaction follows a consecutive pathway in which the intermediate adrenochrome remains stable for few minutes, and then undergoes further reactions to yield adrenolutin and other products. The [Cu(adrenochrome)]$^+$ complex is stable for a few hours. Studies on the effects of cetyltrimethylammonium bromide (CTAB) and sodium dodecyl sulfate (SDS) on the reactivity of both species revealed different behaviors. The micelles of CTAB catalyzed the rates of autoxidation for both species, whereas SDS micelles inhibited the autoxidation of adrenaline but catalyzed the rate of autoxidation of [Cu(adrenaline)]$^{2+}$. Addition of the reactive counterion surfactant, cetyltrimethylammonium hydroxide (CTAOH) initially increased the rate constant with the increasing [CTAOH], until it reached a plateau for k_ψ−[CTAOH]. Salts such as NaCl, NaBr, tetramethyl ammonium bromide, and tetraethyl ammonium bromide increased the rate when added at lower concentrations, but had negligible effect at higher concentrations. The results obtained in micellar media were treated according to Berezin's Pseudophase Model. The various kinetic parameters for the reactions occurring in aqueous and in micellar media are reported.

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Introduction

Adrenaline (Epinephrine) and norepinephrine are catecholamines containing oxidizable catechol and basic amine groups and are of clinical interest in the investigation of tumors of neurological origin. These catecholamines regulate myocardial contractility and metabolism; they play a prominent role in cardiac physiology [1] and have been used effectively for the treatment of heart failure. The autoxidation of the amine group, with the formation of oxygen free radical byproducts, is viewed as a major event in catecholamine cardiomyopathy during postischemic reperfusion [2, 3]. The autoxidation of catecholamines at neutral pH is extremely slow or nonexistent, but becomes faster at pH values above 8 [4]. The oxidation of catecholamines is a rather complex process which involves formation of quinone, hydroquinone, and semiquinone species [5, 6]. Catecholamines, after conversion to semiquinone, disproportionate to form the corresponding *ortho*-quinone; the latter undergoes an irreversible 1,4-intramolecular cyclization leading to the formation of an unstable leucoaminochrome which is rapidly oxidized to an aminochrome [7, 8]. The major products formed during the autoxidation of adrenaline are adrenochrome and adrenolutin. However, other products are also formed, but are relatively unstable and undergo further transformation to dimers and oligomers [9]. Sokoloski and Higuchi [10] reported the kinetics of degradation of adrenaline but were unable to present a complete mechanistic sequence. They suggested that the reaction is extremely complex in nature and involves free radical pathways. The antioxidant activity and radical scavenging activity of l-adrenaline have been investigated by Ilhami [11], who studied the antioxidant activity and mechanism using various in vitro antioxidant assays such as 1,1-diphenyl-2-picrylhydrazyl (DPPH·), 2,2-azino-bis(3-ethylbenzthiazoline-6-

sulfonic acid) (ABTS), *N*,*N*-dimethyl-*p*-phenylenediamine ($DMPD^{\cdot+}$), superoxide anion radicals, hydrogen peroxide, total antioxidant activity, iron (II) and iron (III), copper (II) chelating activity etc.

Micelles and other associated colloids have been widely used as reaction media [12–14] as they are capable of both catalyzing and inhibiting [15, 16] reaction rates, depending upon the nature of interaction between the surfactant and reactants. They play a critical role in the dispersion and/or localization of charges on the activated complex and/or intermediates. Thus, the micelles can influence the reaction rates, equilibria, and concentrations of reactants in the interfacial region [19–25]. Surfactant aggregates can also serve as mimic for biological systems [15].

Copper(II) plays an important role in the reactions of catecholamines and catechol–amino acids in neurological systems [16]. Copper(II) can form complexes with adrenaline [17, 18] and so modify its reactivity. Therefore, keeping in view of the significance of copper(II) and adrenaline in the biological systems, we have studied the kinetics of autoxidation of adrenaline in the absence and the presence of copper(II). The influence of copper(II) on the autoxidation and binding of adrenaline with micelles have been explored and are presented in this paper.

Experimental

Materials

1-(3,4-Dihydroxyphenyl)-2-methylamino ethanol (adrenaline, 95 %, Aldrich, USA), sodium dodecyl sulfate (SDS, 99 %, BDH, England), cetyltrimethylammonium bromide (CTAB, 99 %, BDH, England), sodium chloride (99.9 %, Merck, Germany), and sodium bromide (99 %, BDH, England) were used without further purification. Cetyltrimethylammonium hydroxide (CTAOH) was synthesized and recrystallized in the laboratory. Tetramethyl ammonium bromide (99 %, Sigma, USA), tetraethyl ammonium bromide (99 %, Sigma, USA), copper(II) sulfate ($CuSO_4.5H_2O$, 99 %, BDH, England), and sodium hydroxide of AnalaR grade were used for the experiments. Deionized double-distilled water (specific conductance: 1–2 $\times$ 10^{-6} Ω^{-1} cm^{-1}) was used as a solvent.

Kinetic measurements

The kinetics was followed by monitoring the absorbance at λ_{max} (290 and 300 nm in the presence and the absence of Cu^{2+}, respectively) for the appearance of an intense yellow color as a function of time, using a PerkinElmer Lambda 650 UV–visible spectrophotometer. The temperature was maintained at 25.0 ± 0.1 °C using an L.K.B. 2209 multitemperature water bath. The observed first-order rate constant for the formation of yellow adrenochrome was obtained from slopes of plots ln ($A_\infty - A_t$) versus time. The kinetic experiments were performed until the reaction was completed to 3–4 half-lives. All the values of rate constants (in the absence and presence of Cu^{2+}) and k_ψ (in the presence of surfactants) were obtained from linear plots with average linear regression coefficient, $r^2 \geq 0.99$. The autoxidation of adrenaline was carried out under pseudo first-order conditions using sodium hydroxide in large excess over adrenaline. Each kinetic run was repeated at least 3 times, and the observed results were consistent to within ±5 %. Critical micelle concentrations for the surfactants under the reaction conditions were determined using a Kruss Type 10 tensiometer.

Results and discussion

Autooxidation of adrenaline in aqueous alkali

Repetitive scans for the autoxidation of adrenaline (1.0×10^{-4} mol dm^{-3}) in 5.0×10^{-3} mol dm^{-3} NaOH (Fig. 1) indicated that an intense yellow color with λ_{max} at 300 nm reaches a maximum in ~30 min, remains stable for few minutes, and then starts to decay. The reaction followed a consecutive pathway in which an intermediate adrenochrome is formed (species **5** in Scheme 1). The adrenochrome undergoes further reactions to yield adrenolutin, dimers, and other products [9]. The pathway is summarized in Scheme 1.

The repetition of the same experiment in the presence of 4.0×10^{-3} mol dm^{-3} Cu^{2+} (Fig. 2) showed that the

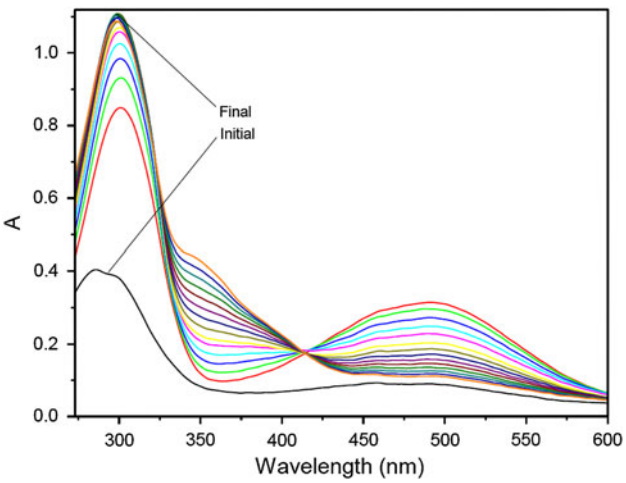
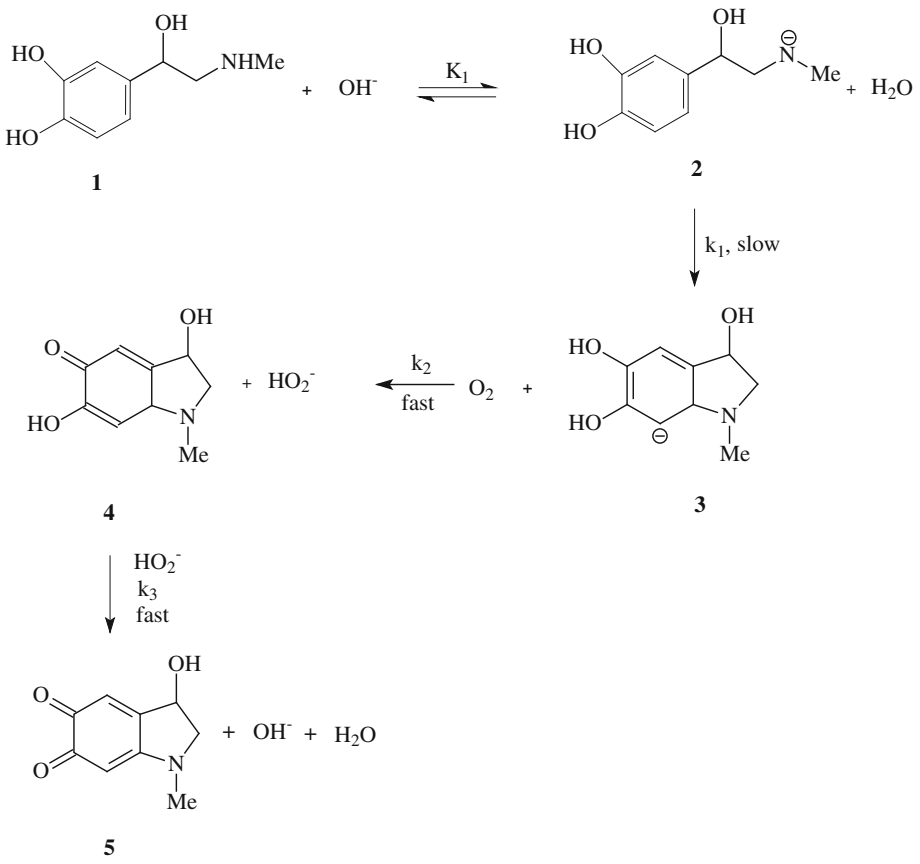


Fig. 1 Repetitive scan for the autoxidation of adrenaline for the formation of adrenochrome. Reaction conditions: [adrenaline] =1.0×10^{-4} mol dm^{-3}, [NaOH] = 5.0×10^{-3} mol dm^{-3}, temperature = 25.0 ± 0.1 °C

Scheme 1 The proposed mechanism of the autoxidation of adrenaline catalyzed by NaOH



intermediate adrenochrome is somewhat more stable and the yellow color (with $\lambda_{max} = 290$ nm) was observed to be stable over the next 2 h (the time up to which spectra were recorded). Plots of log (absorbance) versus time for different initial concentrations (in the range of 1.0–12.0 $\times$ 10^{-4} mol dm^{-3}) of adrenaline and $[Cu(adrenaline)]^{2+}$ at fixed concentration of sodium hydroxide (5.0 $\times$ 10^{-3} mol dm^{-3}) at 25.0 $\pm$ 0.1 °C gave parallel straight lines. Thus, the constant values of k_{obs} indicate that the reaction follows first-order kinetics with respect to adrenaline or its copper complex. The values of the rate constant increased linearly with increasing [NaOH] from 1.0 $\times$ 10^{-3} to 1.0 $\times$ 10^{-2} mol dm^{-3} at fixed concentration of adrenaline (1.0 $\times$ 10^{-4} mol dm^{-3}) or $[Cu(adrenaline)]^{2+}$ (1.0 $\times$ 10^{-4} mol dm^{-3}). Plots of log k_{obs} versus log [adrenaline] (or log $[Cu(adrenaline)]^{2+}$) gave straight lines with slopes 0.99 and 0.78, indicating that the reaction is first order in [adrenaline] and fractional order in $[Cu(adrenaline)]^{2+}$. West [26] proposed that the presence of oxygen is essential for the autoxidation of adrenaline to form adrenochrome. The dissolved O_2 present in solution oxidizes the two phenolic hydroxyl groups of adrenaline. The complexation of Cu^{2+} with the amino group of adrenaline is rapid [18, 27, 28], and the species **6** existing in alkaline medium is shown in Scheme 2, which shows our proposed mechanism in the light of the result obtained.

The reaction is initiated by the attack of OH^- on $[Cu(adrenaline)]^{2+}$ to give intermediate **7.** The anionic complex **7** slowly undergoes cyclization to give

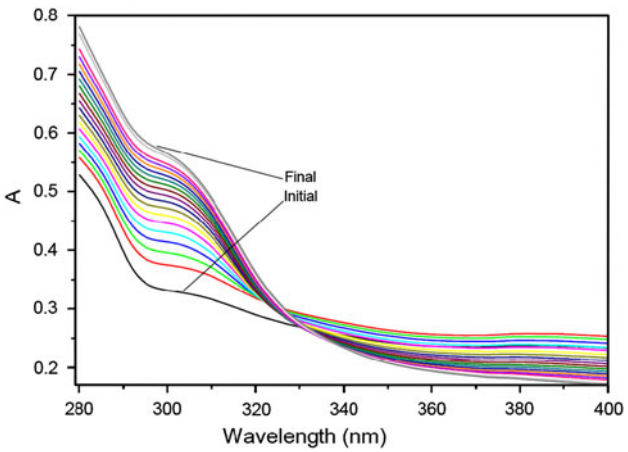
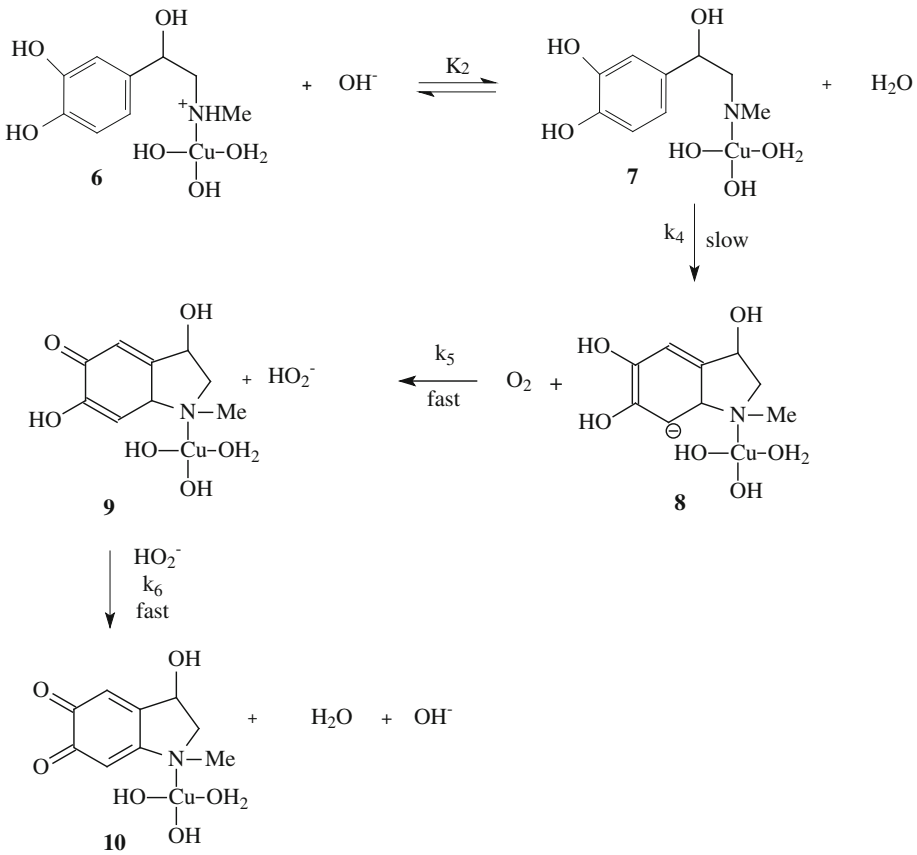


Fig. 2 Repetitive scan for the autoxidation of $[Cu(adrenaline)]^{2+}$ complex. Reaction conditions: $[Cu(adrenaline)]^{2+}$ = 1.0 $\times$ 10^{-4} mol dm^{-3}, [NaOH] = 5.0 $\times$ 10^{-3} mol dm^{-3}, temperature =25.0 $\pm$ 0.1 °C

Scheme 2 The proposed mechanism of the autoxidation of $[Cu(adrenaline)]^{2+}$ catalyzed by NaOH



intermediate **8**. Molecular oxygen then attacks the quinol group of adrenaline to yield the adrenoquinone complex of copper **9**, followed by the adrenochrome complex **10**. The reaction follows free radical pathways [1, 29] for the formation of **10**. The following rate Eqs. (1 and 2) were obtained for the autoxidation of adrenaline and copper adrenaline complex, respectively, corresponding to the proposed mechanisms (Schemes 1, 2):

$$\frac{1}{k_{obs}} = \frac{1}{K_1[OH^-]} + \frac{1}{k_1} \quad (1)$$

$$\frac{1}{k_{obs}} = \frac{1}{K_2[OH^-]} + \frac{1}{k_4} \quad (2)$$

According to the both rate equations, a plot of $1/k_{obs}$ versus $1/[OH^-]$ should give a straight line (Fig. 3) with slope $(1/K_1)$ and intercept $(1/k_1)$. The values of k_1 and k_4 for adrenaline and the Cu(II)-adrenaline complex were obtained from the intercept and are given in Table 1. The values of the equilibrium constants, K_1 (for adrenaline) and K_2 (for copper complex), were obtained from the slope and are also presented in Table 1.

Coordination of adrenaline to the copper(II) center results in a decrease in electron density on the nitrogen atom, facilitating release of the NH proton. Hence, the reaction rate in the presence of copper increases. The

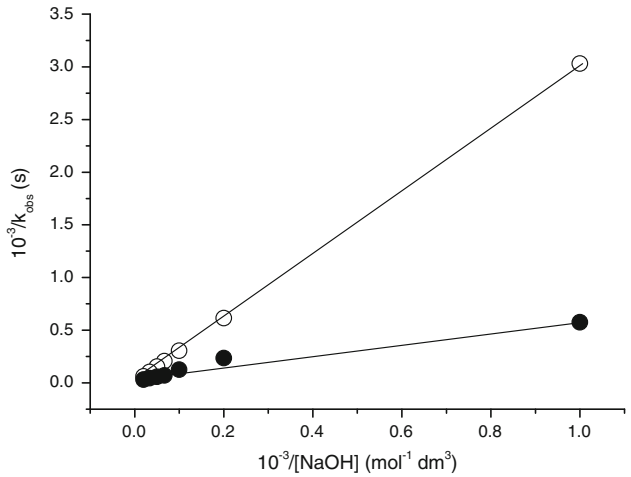


Fig. 3 Plot of $1/k_{obs}$ versus 1/[NaOH] for the autoxidation of adrenaline (*open circle*) and $[Cu(adrenaline)]^{2+}$ (*filled circle*) in the aqueous medium. Reaction conditions: [adrenaline] = 1.0×10^{-4} mol dm^{-3}, $[C(adrenaline)]^{2+} = 1.0 \times 10^{-4}$ mol dm^{-3}, temperature = 25.0 ± 0.1 °C

obtained values of k_4 (Table 1) for the cyclization reaction are actually lower for $[Cu(adrenaline)]^{2+}$ than for adrenaline. This is because coordination to Cu^{2+} may lower the electron density on the nitrogen anion, making it a poorer nucleophile for attack on the ring. The value of the

Table 1 Values of rate constants and equilibrium constants for adrenaline and $[Cu(adrenaline)]^{2+}$ in the aqueous NaOH and micellar media

Medium	10^2 k_1 (s^{-1})		K_2 (mol dm^{-3})	
	Adrenaline	$[Cu(adrenaline)]^{2+}$	Adrenaline	$[Cu(adrenaline)]^{2+}$
NaOH	34.56 ± 1.34	2.03 ± 0.32	0.33 ± 0.02	1.85 ± 0.62
CTAB	12.36[a] ± 0.87	3.00 ± 0.22	3.02 ± 0.06	12.01 ± 0.91
SDS	0.81 ± 0.02	2.19 ± 0.14	0.21 ± 0.04	6.14 ± 0.74

Reaction conditions: [adrenaline] = 1.0×10^{-4} mol dm^{-3}, [SDS] = 1.0×10^{-2} mol dm^{-3}, [CTAB] = 2.0×10^{-2} mol dm^{-3}

[a] [CTAB] = 1.0×10^{-2} mol dm^{-3}, $[Cu(adrenaline)]^{2+}$ = 1.0×10^{-4} mol dm^{-3}, temperature = 25.0 ± 0.1 °C

Table 2 Values of the observed rate constants and calculated rate constants for the autoxidation of adrenaline and $[Cu(adrenaline)]^{2+}$ in the alkaline medium using Eqs. 1 and 2 and the parameters given in Table 1 at different concentrations of NaOH

10^3 [NaOH] (mol dm^{-3})	$10^3(k_{adr})_{obs}$ (s^{-1})	$10^3(k_{adr})_{calc}$ (s^{-1})	$10^3(k_{Cu\text{-}adr})_{obs}$ (s^{-1})	$10^3(k_{Cu\text{-}adr})_{calc}$ (s^{-1})
1.0	0.33 ± 0.06	0.33	1.74 ± 0.08	1.70
5.0	1.62 ± 0.11	1.64	4.26 ± 0.14	5.35
10.0	3.28 ± 0.09	3.27	7.96 ± 0.16	8.67
15.0	4.87 ± 0.14	4.88	14.22 ± 0.12	13.72
20.0	6.55 ± 0.12	6.48	17.34 ± 0.13	18.10
30.0	9.76 ± 0.16	9.63	22.54 ± 0.12	24.86
50.0	15.98 ± 0.15	15.75	32.12 ± 0.14	33.66

equilibrium constants (K_2) is higher for $[Cu(adrenaline)]^{2+}$ than for adrenaline (K_1) because Cu^{2+} facilitates the removal of H^+ ions from the amino nitrogen, as described earlier. Thus, the overall value of k_{obs} is higher for $[Cu(adrenaline)]^{2+}$ than for adrenaline. The observed and calculated values of rate constants (k_{obs} and k_{calc}) are presented in Table 2. The values of the rate constants were calculated from the parameters given in Table 1. Increasing concentrations of sodium chloride, sodium bromide, tetramethyl ammonium bromide, and tetraethyl ammonium bromide (Fig. 4) slightly increased the values of rate constant in the lower concentration range (i.e. 5–30 mmol dm^{-3}); similar behavior of these salts was observed in the autoxidation of benzoin in alkaline solution [24, 30]. The formation of an ion pair helps to stabilize the anion as shown in Scheme 3 and so increases the rate of reaction. Further increases in [salt] did not influence the rate of reaction, indicating that the autoxidation of adrenaline follows either a molecular or free radical mechanism.

Autoxidations in micellar media

The influence of the cationic surfactants cetyltrimethylammonium bromide (CTAB), cetyltrimethylammonium hydroxide (CTAOH), and anionic surfactant sodium dodecyl sulfate (SDS) on the reaction rate for the autoxidation of adrenaline was studied at varying concentrations of surfactant. The addition of CTAB increased the values of pseudo first-order rate constants in the lower concentration range for both the adrenaline and $[Cu(adrenaline)]^{2+}$. Further increases in the concentration of CTAB increased the rate constant to a maximum value, and then, it decreased with still further increase in [CTAB]. The decrease in the rate constant was sharp for adrenaline, while for $[Cu(adrenaline)]^{2+}$ the rate constant did not decrease much. This behavior is typical of a bimolecular reaction catalyzed by non-reactive counter ion micelles (Fig. 5). SDS inhibited the rate of autoxidation of adrenaline (Fig. 6), while CTAOH gave a plateau-like curve for the plot of k_ψ versus [CTAOH] (Fig. 7). The variation in rate constant for CTAB and SDS for the autoxidation of $[Cu(adrenaline)]^{2+}$ displayed a maximum type behavior with maximum values at 2.0×10^{-2} mol dm^{-3} for [SDS] and 7.0×10^{-3} mol dm^{-3} for [CTAB].

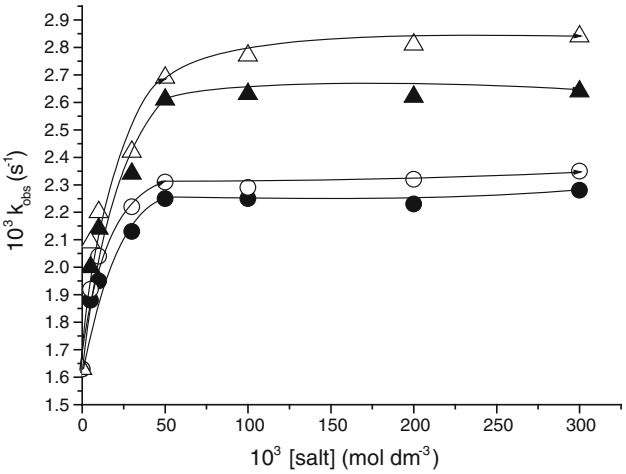
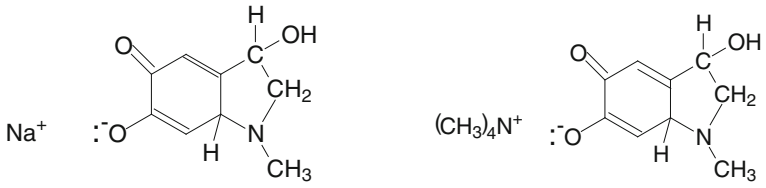


Fig. 4 Plot of k_{obs} versus [salt] for the autoxidation of adrenaline in the aqueous medium. Reaction conditions: [adrenaline] = 1.0×10^{-4} mol dm^{-3}, [NaOH] = 5.0×10^{-3} mol dm^{-3}, NaBr (*filled circle*), NaCl (*open circle*), Tetraethyl ammonium bromide (*filled triangle*), Tetramethyl ammonium bromide (*open triangle*), temperature = 25.0 ± 0.1 °C

The results obtained for the autoxidation of adrenaline and $[Cu(adrenaline)]^{2+}$ in the presence cationic micelles of CTAB can be explained on the basis of the pseudophase

Scheme 3 Formation of an ion pair between cations (Na^+ and $(CH_3)_4N^+$ the intermediate anion 4



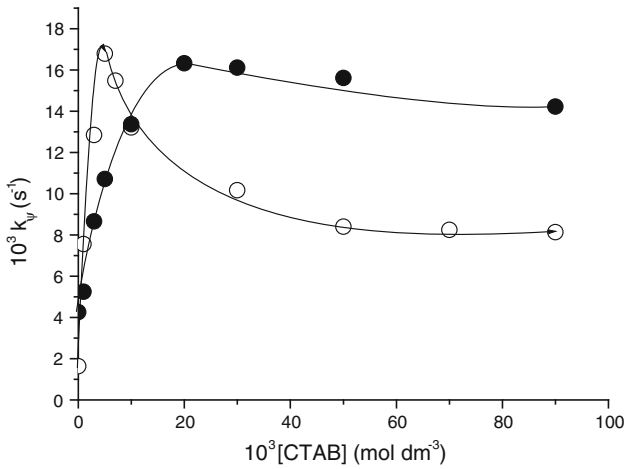


Fig. 5 Plot of k_ψ versus [CTAB] for the autoxidation of adrenaline (*open circle*) and $[Cu(adrenaline)]^{2+}$ (*filled circle*). Reaction conditions: [adrenaline] = 1.0×10^{-4} mol dm^{-3}, $[Cu(adrenaline)]^{2+}$ = 1.0×10^{-4} mol dm^{-3}, [NaOH] = 5.0×10^{-3} mol dm^{-3}, temperature = 25.0 ± 0.1 °C

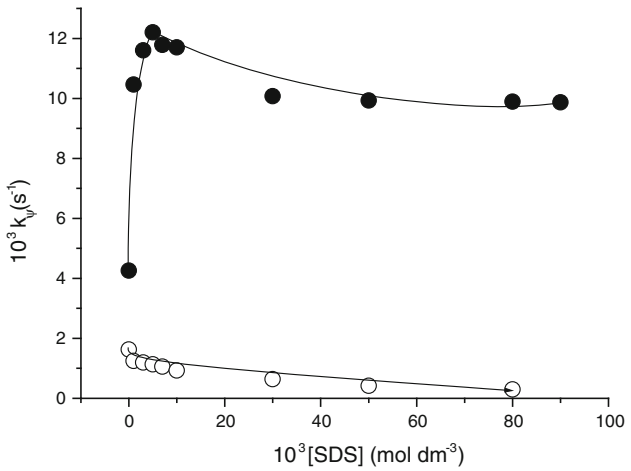


Fig. 6 Plot of k_ψ versus [SDS] for the autoxidation of adrenaline (*open circle*) and $[Cu(adrenaline)]^{2+}$ (*filled circle*). Reaction conditions: [adrenaline] = 1.0×10^{-4} mol dm^{-3}, $[Cu(adrenaline)]^{2+}$ =1.0×10^{-4} mol dm^{-3}, [NaOH] = 5.0×10^{-3} mol dm^{-3}, temperature = 25.0 ± 0.1 °C

ion-exchange model, in which the substrate is considered to be distributed between the aqueous and micellar phases. This distribution is governed by the values of the binding constant, K_s. The distribution of reactive OH^- ions in both pseudophases is based on the principle of ion exchange in

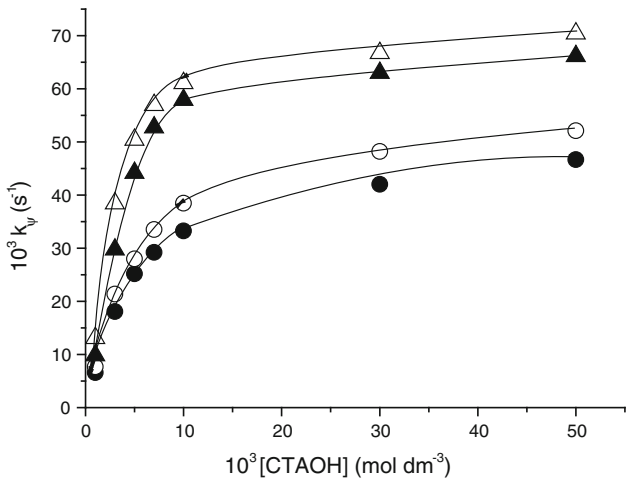


Fig. 7 Plot of k_ψ versus [CTAOH] for the autoxidation of adrenaline in the absence (*filled circle*) and the presence of NaOH (*open circle*; 1.0×10^{-3} mol dm^{-3} NaOH, *filled triangle*: 2.0×10^{-3} mol dm^{-3} NaOH, *open triangle*; 3.0×10^{-3} mol dm^{-3} NaOH), [adrenaline] = 1.0×10^{-4} mol dm^{-3}, temperature = 25.0 ± 0.1 °C

which the surfactant aggregates act as an ion exchanger. Scheme 4 is used to describe the reactions occurring in the aqueous and micellar phases:

In this Scheme 4, D_n is the micellized surfactant (i.e. [total surfactant]—cmc), k_w' and k_m' are the first-order rate constant for the autoxidation (of adrenaline or $[Cu(adrenaline]^{2+}$) in the aqueous and micellar pseudophases, respectively, and K_s is the binding constant for the substrate (adrenaline or $[Cu(adrenaline]^{2+}$), S to the micelle, which is given by

$$K_s = \frac{[S_m]}{[S_w][D_n]} \tag{3}$$

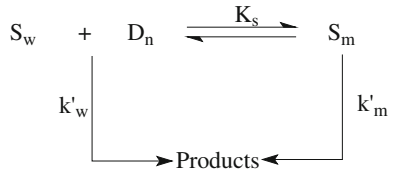
S_m and S_w represent adrenaline or $[Cu(adrenaline]^{2+}$ bound to the micellar and aqueous pseudophases, respectively.

The observed rate constant in the presence of surfactant is given by

$$k_\psi = \frac{k'_w + k'_m K_s [D_n]}{1 + K_s [D_n]} \tag{4}$$

k'_w and k'_m in terms of reactant OH^- ion concentration can be given by

$$k'_w = k_w \left[OH^-_w\right] \tag{5}$$



Scheme 4 Mechanism of the micelles catalyzed autodixation of adrenaline and $[Cu(adrenaline)]^{2+}$

$$k'_{m} = \frac{k_m [OH^-_m]}{[D_n]} \tag{6}$$

where k_m is defined in terms of the molar ratio of OH^- ions bound to the micellar head-groups.

In the present case, Br^- (the counterion of CTAB) and reactive OH^- compete for the charged micellar surface. Their distribution in the Stern region of the micelles can be predicted using a model proposed by Romsted [12, 13], in which the ions bind to the micelle through a process of ion-exchange similar to that occurring in ion-exchange resins. For OH^- as reactive ion and Br^- as micelle counterion, the ion-exchange equilibrium can be expressed as

$$OH^-_W + Br^-_m \overset{K^{OH}_{Br}}{\rightleftharpoons} OH^-_m + Br^-_W \tag{7}$$

Hence

$$K^{OH}_{Br} = \frac{[OH^-_m][Br^-_w]}{[OH^-_w][Br^-_m]} \tag{8}$$

Here, $Br^-_m$and Br^-_w are the surfactant counterions in the micellar and aqueous phases, respectively. Similarly, the β parameter may be defined as the neutralized fraction of the micellar head-groups

$$\beta = m_{OH} + m_{Br} \tag{9}$$

where m_{OH} and m_{Br} are the neutralized fractions of the micellar head-group with reactive (OH^-) and non-reactive (Br^-) ions. Then,

$$m_{OH} = \frac{[OH^-_m]}{[D_n]} \tag{10}$$

$$m_{Br} = \frac{[Br^-_m]}{[D_n]} \tag{11}$$

According to Eqs. 5–8 and Scheme 3, the first-order rate constant equation can be written as

$$k_\psi = \frac{k_w [OH^-_T] + (k_m K_s - k_w) m_{OH} [D_n]}{1 + K_s [D_n]} \tag{12}$$

where

$$[OH^-_T] = [OH^-_w] + [OH^-_m] \tag{13}$$

Similarly,

$$[Br^-_T] = [Br^-_w] + [Br^-_m] \tag{14}$$

The following quadratic expression was used to evaluate the value of m_{OH} for the determination of micelle-bound hydroxide ions by considering the ion-exchange model for ion-exchange resins, keeping β constant

$$m^2_{OH} + m_{OH}\left[\frac{[OH^-_T] + K^{OH}_{Br}[Br^-_T]}{(K^{OH}_{Br} - 1)[D_n]} - \beta\right] - \frac{\beta[OH^-_T]}{(K^{OH}_{Br} - 1)[D_n]} = 0 \tag{15}$$

The experimental observations demonstrate that the presence of micelles influences the reaction rate by inhibiting (adrenaline in SDS) or by accelerating (adrenaline in CTAB and $[Cu(adrenaline)]^{2+}$ in CTAB and SDS) the rate of autoxidation. The micelles are dynamic in nature, and the association of surfactant molecules into micelles and dissociation into monomers are faster than the rate of autoxidation. Therefore, it can be assumed that a large proportion of reactions occur in the micellar media, and the reactions occurring in aqueous media can be neglected by comparison. Hence, Eq. (12) can be rewritten as

$$k_\psi = \frac{k_m K_s m_{OH} [D_n]}{1 + K_s [D_n]} \tag{16}$$

Rearranging Eq. (16) gives

$$\frac{m_{OH}}{k_\psi} = \frac{1}{k_m} + \frac{1}{k_m K_s [D_n]} \tag{17}$$

Thus, plots of m_{OH}/k_ψ versus $1/[D_n]$ for the autoxidation of adrenaline and $[Cu(adrenaline)]^{2+}$ occurring in the micellar media of SDS and CTAB gave straight lines. The values of k_m and K_s were calculated from the intercept and slope, respectively, and are given in Table 3. The observed and calculated values of rate constants (using Eqs. 10–15) are compared in Table 4 and show good agreement.

The results for the autoxidation of adrenaline in reactive micelles of CTAOH were treated by using the following relationship of the mass action model [30–32]

$$OH^-_W + D^-_n \overset{k'_{OH'}}{\rightleftharpoons} OH^-_M \tag{18}$$

Or,

$$K'_{OH} = \frac{[OH^-_M]}{[OH^-_W]([D_n] - [OH^-_M])} \tag{19}$$

Rearrangement of Eq. (19) gives Eq. (20)

$$K'_{OH}[OH^-_M]^2 - \left(1 + K'_{OH}[D_n] + K'_{OH}[OH^-_T]\right)[OH^-_M] + K'_{OH}[D_n][OH^-_T] \tag{20}$$

The value of $[OH_m]$ was obtained on solving the quadratic Eq. (20). Equation (12) on rearrangement and in terms of $[OH_m]$ can be written as

Table 3 Fitted parameters of the kinetic results for the base catalyzed autoxidation of adrenaline and $[Cu(adrenaline)]^{2+}$ in CTAB and SDS

Surfactant	10^3 cmc (mol dm^{-3})	β	Adrenaline			$[Cu(adrenaline)]^{2+}$		
			K_X^{OH} (X = Br/Cl)	10^2k_m (s^{-1})	K_s	K_X^{OH} (X = Br/Cl)	10^2k_m (s^{-1})	K_s
CTAB	0.8	0.80	16	85 ± 2	49 ± 4	16	348 ± 2	9 ± 2
SDS	0.8	0.81	6	1.38 ± 0.04	157 ± 6	6	51 ± 2	28 ± 4

Reaction conditions: $[NaOH] = 5.0 \times 10^{-3}$ mol dm^{-3}, $[adrenaline] = 1.0 \times 10^{-4}$ mol dm^{-3}, $[Cu(adrenaline)]^{2+} = 1.0 \times 10^{-4}$ mol dm^{-3}, temperature = 25 ± 0.1 °C

Table 4 Values of the observed rate constants and calculated rate constants for the autoxidation of adrenaline and $[Cu(adrenaline)]^{2+}$ in the micellar medium by using Eq. 12 and the parameters given in Table 3

10^3 [Surfactant] (mol dm^{-3})	Adrenaline		$[Cu(adrenaline)]^{2+}$	
	10^3 $(k_\psi)_{obs}$ (s^{-1})	10^3 $(k_\psi)_{calc}$ (s^{-1})	$10^3(k_\psi)_{obs}$ (s^{-1})	10^3 $(k_\psi)_{calc}$ (s^{-1})
(i) CTAB				
1	07.56 ± 0.25	09.18	05.24 ± 0.23	05.51
3	12.84 ± 0.28	14.95	08.66 ± 0.29	09.69
5	16.79 ± 0.26	15.83	10.71 ± 0.24	11.19
7	15.48 ± 0.32	12.85	–	–
10	13.21 ± 0.34	11.60	13.36 ± 0.32	14.20
30	10.17 ± 0.21	09.10	16.32 ± 0.26	16.64
50	08.4 ± 0.22	06.88	16.10 ± 0.32	16.22
70	08.25 ± 0.28	04.90	15.61 ± 0.31	15.86
90	08.13 ± 0.31	04.19	14.22 ± 0.29	15.04
(ii) SDS				
1	1.25 ± 0.06	1.36	10.46 ± 0.23	10.21
3	1.19 ± 0.04	1.17	11.6 ± 0.32	11.58
5	1.13 ± 0.04	1.08	12.2 ± 0.31	12.14
7	1.06 ± 0.05	0.88	11.78 ± 0.37	11.57
10	0.93 ± 0.03	0.84	11.70 ± 0.32	11.68
30	0.64 ± 0.04	0.52	10.07 ± 0.28	10.45
50	0.42 ± 0.03	0.36	09.93 ± 0.26	09.82
80	0.30 ± 0.02	0.25	09.89 ± 0.28	09.75
90	–	–	09.87 ± 0.27	09.70

$$\frac{[OH_m]}{k_\psi} = \frac{1}{k_m K_s} + \frac{[D_n]}{k_m} \quad (21)$$

Thus, a plot of $[OH_m]/k_\psi$ versus $[D_n]$ gave a straight line with slope = $1/k_m$ and intercept = $1/k_mK_s$. The values of k_m, K_s and K'_{OH} were obtained from the plot and are given in Table 5. The values of the binding constant of adrenaline in CTAB are found to be higher than for its copper complex, indicating that the cationic micelles of CTAB have less affinity for the positively charged copper complex. The autoxidation in SDS micelles is extremely slow and almost ceases at high [SDS], while the reaction rate increases for $[Cu(adrenaline)]^{2+}$ in the same SDS micelles and reaches a plateau at higher [SDS]. It may be that the location or orientation of the molecules in SDS micelles is such that it does not favor the reaction. The complexation with copper makes the adrenaline more hydrophilic, and the $[Cu(adrenaline)]^{2+}$ complex may lie near the Stern or Gouy Chapman region of the micelles. As a result, the value of binding constant is decreased, and the reaction rate is increased. The increase in concentration of NaOH in the CTAOH system increases the rate of reaction, but the overall value of rate constant in the micellar region remains in the same order. The binding constant is slightly affected due to high concentration of OH^- in the Stern region.

Conclusions

Adrenaline and its copper complex undergo autoxidation reaction in alkaline media with different rates in the presence of dissolved oxygen. The reaction rates of both species were found to be dependent upon $[OH^-]$. The addition of Cu^{2+} to the adrenaline solution stabilized the intermediate adrenochrome in alkaline medium. Added salts

Table 5 Fitted parameters of the kinetic results for the base catalyzed autoxidation of adrenaline in CTAOH

Reaction conditions: [adrenaline] = 1.0×10^{-4} mol dm^{-3}, temperature = 25 ± 0.1 °C

Surfactant	10^3 [NaOH] (mol dm^{-3})	10^3 cmc (mol dm^{-3})	B	K_{OH}	$10^2 k_m$ (s^{-1})	K_s
CTAOH	0.0	0.8	0.80	34	3.51 ± 0.04	30 ± 3
CTAOH	1.0	0.8	0.80	34	6.09 ± 0.06	15 ± 2
	2.0	0.8	0.80	34	5.71 ± 0.07	24 ± 4
	3.0	0.8	0.80	34	5.91 ± 0.06	25 ± 3

increased the rate of reaction slightly in the lower concentration range by the formation of ion pairs with the added cations in the aqueous medium. Higher concentrations of salts elicited no further change in the rate. The autoxidation reactions follow molecular or free radical pathways. CTAB and CTAOH micelles increased the rate of autoxidation of adrenaline, while SDS micelles inhibited the rate. SDS and CTAB micelles catalyzed the rate of autoxidation of $[Cu(adrenaline)]^{2+}$ in the lower concentration ranges, then reached a plateau at higher concentrations. Further increase in [surfactant] resulted in a slight lowering of the rate constant. The binding constant for $[Cu(adrenaline)]^{2+}$ was higher than the binding constant of adrenaline with surfactants, perhaps due to the charge on the complex.

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