Brij-35 micellar catalysed chloramine-T oxidation of vitamins: A kinetic study

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The kinetics of oxidation of the vitamins (B₁ and B₆) by sodium salt of p-toluene sulfonamide (Chloramine-T) have been studied in presence of a non-ionic surfactant, i.e., polyoxyethylene(23)laurylether (Brij-35) in perchloric acid medium. Catalytic effect of Brij-35 micelle has been observed on the rate of oxidation. The reactions show first order, fractional order and zero-order dependence of rate with respect to chloramine-T, vitamins and HClO₄, respectively. The mechanism in absence as well as in presence of surfactant has been proposed. The spectrophotometric evidence supports the binding/association between chloramine-T and Brij-35 micelle. The kinetic data have also been rationalised in terms of Menger and Portnoy’s kinetic model and binding parameters have been evaluated.

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The redox processes in micellar systems can be considered as models to get insight to electron-transport occurring in biological phenomena because incorporation of the substrate is a prerequisite for both micellar and enzyme catalysis. Many workers have drawn analogies between the two processes.

Among N-haloamines, sodium salt of toluene-p-sulphonamide (CH₃C₆H₄SO₂NNaCl), commonly known as chloramine-T, has widely been used as an oxidant in neutral, acidic and alkaline medium. Chloramine-T is also used as an antiseptic drug and in titrimetric determination of vitamins which are important pharmaceutical substances. Therefore, the study on the kinetics of interactions between chloramine-T and vitamins in micellar media may have the importance in various biotechnological and pharmaceutical disciplines. The kinetics of oxidation of vitamin B₁ (thiamine hydrochloride) and vitamin B₆ (pyridoxine hydrochloride) by chloramine-T in presence of a non-ionic surfactant, viz. polyoxyethylene(23)laurylether (Brij-35) are reported here.

Experimental

Stock solution of chloramine-T (A.R., Thomas Baker, India) was used as received. However, its purity was ascertained by measuring the critical micelle concentration (CMC) from surface tension versus log [Surfactant] plot. The CMC agreed with the reported value, i.e. 9.2×10⁻⁵ mol dm⁻³. The solution of surfactant was prepared in doubly distilled water just before the experiment to avoid ageing. Other reagents, viz. HClO₄, KOH, sodium thiosulphate (hypo), starch, etc. used were of analytical grade. Double distilled (first time from alkaline KMnO₄) deionised water was used throughout.

Appropriate quantities of solutions of vitamins, HClO₄ and surfactant were placed in 100 mL jena glass vessel. The requisite amount of doubly distilled water was added so that the total volume of reaction mixture was 50 mL after adding the chloramine-T solution. The reaction mixture was then placed in a thermostat at desired temperature (±0.1°C). The reaction mixture was allowed to attain the bath temperature and the reaction was then initiated by adding the requisite amount of chloramine-T placed separately in same water bath. Progress of the reaction was followed by determining chloramine-T iodometrically in aliquots withdrawn at regular time intervals. The reaction mixture was homogenous.

To study stoichiometry of the reaction, the reaction mixtures containing a known excess of [chloramine-T] over [vitamin] were kept in presence of fixed amounts of HClO₄ and surfactant at room temperature for 72 h until the reactions were complete. The unreacted amount of chloramine-T left in the reaction mixture showed a 1:1 stoichiometry between chloramine-T and vitamin. The results may be represented by:

RNaCl + R'CH₂OH → RNH₂ + R'CHO + NaCl

where,

R = CH₃\(\text{O-SO}_2^-\)
NH₃, HCl

R' = \(\text{N} = \text{C}_3\text{H}_7\text{N} = \text{C}_3\text{H}_7\text{N} = \text{C}_3\text{H}_7\text{N} = \text{C}_3\text{H}_7\)

in case of vitamin B₁

\(\text{HOH}_2\text{C}_6\text{H}_4\text{N} = \text{OH}\)
in case of vitamin B₆
Presence of aldehyde group in the oxidation product of vitamins was detected by spot tests and by forming its derivative with 2,4-dinitrophenylhydrazine. After completing the reaction, a saturated solution of 2,4-dinitrophenylhydrazine in 2 N HCl was added to the reaction mixture. After keeping it for 12 h in a refrigerator, the yellow precipitate of 2,4-dinitrophenylhydrazone of aldehyde product was observed. The aldehydes as the oxidation products of vitamins are reported in literature also.

**Results and discussion**

The reactions were initially fast and log \((a-x)\) versus time plots [where \((a-x)\) represents the unreacted amount of chloramine-T at any time \(t\)] showed initially a curvature up to nearly 10-20\% of unreacted amount of chloramine-T at any time \(t\) versus time plots [where (variation in [Substrate], [Oxidant] and [HClO concentration of the reactants in absence and in presence of Brij-35 and CMC of Brij-35 = 2.0×10\(^{-4}\) mol dm\(^{-3}\) for vitamin B\(_6\) and 8.0×10\(^{-4}\) mol dm\(^{-3}\) for vitamin B\(_4\); CMC of Brij-35 = 9.2×10\(^{-5}\) mol dm\(^{-3}\)] has also been observed. The aldehydes as the oxidation products of vitamins are reported in literature also.

The kinetic runs have been made at various initial concentrations of the reactants in absence and in presence of surfactant. The kinetic results for variation in [Substrate], [Oxidant] and [HClO\(_4\)] in absence and in presence of surfactant were almost similar. Therefore, the kinetic results in presence of surfactant are reported. The observed pseudo-first order rate constant in chloramine-T \((k_w, \text{ in absence of Brij-35 and } k_w \text{ in presence of Brij-35})\) were reproducible within ±5\% in replicate kinetic runs.

![Table 1](image)

<table>
<thead>
<tr>
<th>[CAT]×10(^3) (mol dm(^{-3}))</th>
<th>[HClO(_4)]×10(^3) (mol dm(^{-3}))</th>
<th>(k_w)×10(^5) (s(^{-1}))</th>
<th>Vitamin B(_1)</th>
<th>Vitamin B(_6)</th>
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<tr>
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<td>2.80</td>
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<td>2.68</td>
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</tr>
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<td>2.0</td>
<td>2.30</td>
<td>2.68</td>
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<td>2.35</td>
<td>2.70</td>
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<td>2.50</td>
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</tr>
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<td>4.0</td>
<td>2.35</td>
<td>2.40</td>
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<td>6.0</td>
<td>2.30</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
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<td>8.0</td>
<td>2.35</td>
<td>2.45</td>
<td></td>
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</table>

The effect of [CAT] and [HClO\(_4\)] on the rate constants in presence of Brij-35 at 40°C [\([\text{vitamin}] = 2.0×10^{-2} \text{ mol dm}^{-3}\); \([\text{Brij-35}] = 2.0×10^{-3} \text{ mol dm}^{-3}\) for vitamin B\(_1\) and 8.0×10\(^{-4}\) mol dm\(^{-3}\) for vitamin B\(_6\); CMC of Brij-35 = 9.2×10\(^{-5}\) mol dm\(^{-3}\)] has also been observed. The observed pseudo-first order rate constant in chloramine-T \((k_w)\) in presence of Brij-35 at various initial concentrations of chloramine-T and H\(^+\) are reported in Table 1. Nearly same value of \(k_w\) at different [chloramine-T] or [H\(^+\)] suggests a first order dependence of rate with respect to [chloramine-T] and a zero order dependence of rate with respect to [H\(^+\)], respectively.

On increasing the concentrations of vitamin in reaction mixture, an increase in \(k_w\) was observed. A plot of log \((k_w)\) versus log [vitamin] was linear with a slope nearly 0.6±0.1 in case of each vitamin, suggesting a fractional order dependence of rate with respect to substrate.

The effect of variation of ionic strength (addition of NaClO\(_4\)) in the reaction mixture had a negligible effect on the rate of oxidation, suggesting the involvement of at least one neutral species in the rate-determining step.

The addition of p-toluene sulphonamide (i.e. RNH\(_2\), reaction product from chloramine-T) had also a negligible effect on the rate of oxidation indicating that chloramine-T (RNNaCl) and p-toluene sulphonamide (RNH\(_2\)) are not involved in the reversible step.

The effect of surfactant [Brij-35] on the rate of oxidation has been studied over a wide concentration range of the surfactant and at three different temperatures (30, 40 and 50°C). The rate surfactant profile, i.e. the plot of \((k_w)\) versus [Brij-35] \((\text{Fig. 1})\) was linear with a positive intercept suggesting that the rate is proportional to \(k' + k''[\text{Surfactant}]\), where \(k'\) and \(k''\) are the rate constants in absence and in presence of the surfactant, respectively. The observed value of rate in absence of the surfactant, i.e. when [surfactant] = 0, was matching with value of the intercept of the plot of \((k_w)\) versus [Brij-35] \((\text{Fig. 1})\). It was also observed that at very high concentration of the surfactant, the plot of \(k_{obs}\) versus [surfactant] showed a deviation from the linearity.

In order to evaluate the activation parameters, the rate constants have been by measured at different temperatures, viz. 30, 40 and 50°C in presence of the surfactant. The activation parameters are given in Table 2. A decrease in energy of activation \((\Delta E^\#)\) in presence of Brij-35 is in favour of catalysis by Brij-35. A more negative value of \(\Delta S^\#\) (entropy of activation) indicates the more compactness of transition state in presence of the surfactant. Nearly same value of \(\Delta G^\#\) (96.0 ± 1.0 kJ mol\(^{-1}\)) in absence as well as in presence of the surfactant, has been observed, which indicates the same mechanism in aqueous and micellar medium.
In order to confirm any association or binding between the surfactant and the reactants, the spectrum of the surfactant and reactants were taken on a double beam spectrophotometer (Systronics 2203, India). A solution of Brij-35 (2×10^{-4} \text{ mol dm}^{-3}) in presence of HClO_4 (1.0×10^{-3} \text{ mol dm}^{-3}) gave a peak value at 225 nm. A shift in peak value from 225 nm to 228 nm was observed when the chloramine-T was added in the solution. The absorbance of a series of solutions containing a fixed amount of Brij-35 (2.0×10^{-4} \text{ mol dm}^{-3}) and HClO_4 (1.0×10^{-3} \text{ mol dm}^{-3}) and a varying amount of vitamin were also measured under similar conditions. No change in absorbance of solutions was observed indicating absence of any association between surfactant and vitamin.

Chloramine-T behaves as a strong electrolyte in aqueous solutions and ionises as given in Eq.(1):

\[
\text{RNNaCl} \overset{K_a}{\rightarrow} \text{RNCl}^- + \text{Na}^+ \quad \text{... (1)}
\]

(\text{where } R = \text{CH}_3\text{C}_6\text{H}_4\text{SO}_2^- \text{ group})

It has also been observed by Rao and coworkers that, at higher acid strength, RNHCl is further protonated according to Eq. (3):

\[
\text{RNHCl} + \text{H}^+ \overset{K_c}{\rightarrow} \text{RNH}_2^+\text{Cl}^- \quad \text{... (3)}
\]

Thus, in acidic medium chloramine-T itself, RNHCl and RNH_2^+Cl^- are possible oxidizing species of chloramine-T.

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**Table 2 — Activation parameters in absence and in presence of surfactant**

<table>
<thead>
<tr>
<th></th>
<th>(\Delta E_a \pm 1.0) (kJ mol(^{-1}))</th>
<th>(\log A)</th>
<th>(\Delta H \pm 0.5) (kJ mol(^{-1}))</th>
<th>(\Delta S \pm 1.0) (JK(^{-1})mol(^{-1}))</th>
<th>(\Delta G \pm 1.0) (kJ mol(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>In absence of surfactant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitamin B(_1)</td>
<td>56.2</td>
<td>5.48</td>
<td>53.6</td>
<td>142.2</td>
<td>97.9</td>
</tr>
<tr>
<td>Vitamin B(_6)</td>
<td>79.2</td>
<td>9.30</td>
<td>76.5</td>
<td>66.5</td>
<td>97.2</td>
</tr>
<tr>
<td>In presence of surfactant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitamin B(_1)</td>
<td>35.2</td>
<td>2.22</td>
<td>32.5</td>
<td>202.5</td>
<td>95.9</td>
</tr>
<tr>
<td>Vitamin B(_6)</td>
<td>63.8</td>
<td>7.18</td>
<td>61.2</td>
<td>107.7</td>
<td>95.0</td>
</tr>
</tbody>
</table>

The absorbance of a series of solutions containing a fixed amount of Brij-35 (2.0×10^{-4} \text{ mol dm}^{-3}) and HClO_4 (1.0×10^{-3} \text{ mol dm}^{-3}) and a varying amount of vitamin were also measured under similar conditions. No change in absorbance of solutions was observed indicating absence of any association between surfactant and vitamin.
Dichloramine-T\textsuperscript{14} or HOCl\textsuperscript{15} has also been considered as the reacting species of chloramine-T. Dichloramine-T or HOCl is produced due to disproportionation or hydrolysis, respectively, of RNHCl as follows:

\[
K_d = 6.1 \times 10^{-2} \text{ at } 25^\circ C \quad \cdots (4)
\]

\[
K_h = 4.9 \times 10^{-8} \text{ at } 25^\circ C \quad \cdots (5)
\]

On considering that NH\textsubscript{3}\textsuperscript{+}Cl is the reactive species of the chloramine-T, an acceleration effect of H\textsuperscript{+} on the rate is expected. Further, if RNCl\textsubscript{2} or HOCl is the reactive species, a second order dependence of rate with respect to chloramine-T and a retarding effect of RNH\textsubscript{2} (p-sulphonamide) on the rate is expected. The experimental results (i.e., a first order dependence of rate with respect to chloramine-T, negligible effect of H\textsuperscript{+} or RNH\textsubscript{2} on the rate) are not in favour of RNCl\textsubscript{2}, HOCl or RN\textsubscript{2}Cl as the reactive species of chloramine-T. Since chloramine-T exists as free acid\textsuperscript{16} (RNHCl) in acidic medium, RNHCl may be considered as the only reactive species of chloramine-T in present conditions.

Formation of aggregation, i.e., micelle of the surfactant and incorporation/association/solubilisation of the substrate with the micelle is well reported in the literature\textsuperscript{17-19}. The spectrophotometric evidence is in favour of association of chloramine-T with surfactant micelle.

On the basis of experimental results and spectrophotometric evidence of association for the chloramine-T with surfactant, a common mechanism for the oxidation of vitamins by chloramine-T is proposed (Scheme 1).

According to Scheme 1, the rate of disappearance of chloramine-T may be given as:

\[
-\frac{d[\text{CAT}]}{dt} = k_2[X_T] + k_4[Y_T][\text{vitamin}] \quad \cdots (6)
\]

Again,

\[
[X_T] = K_1[\text{CAT}][\text{vitamin}] \quad \text{from step (i)}
\]

and

\[
[Y_T] = K_3[\text{CAT}][\text{Brij-35}] \quad \text{from step (iii)}
\]

Therefore, the rate law (6) may be written as:

\[
-\frac{d[\text{CAT}]}{dt} = [\text{CAT}][\text{vitamin}][k_2K_1 + k_4K_3]\quad \text{from Eq.(3)}
\]

\[
\cdots (7)
\]

Now, the total concentration of chloramine-T at any time may be given as:

\[
[\text{CAT}]_T = [\text{CAT}] + [X_T] + [Y_T] \quad \cdots (8)
\]

On substituting the values of \([X_T]\) and \([Y_T]\) in Eq.(3) and solving it, the value of \([\text{CAT}]\) in terms of \([\text{CAT}]_T\) may be obtained as:

\[
[\text{CAT}] = \frac{[\text{CAT}]_T}{1 + K_1[\text{vitamin}] + K_3[\text{Brij-35}]} \quad \cdots (9)
\]

Therefore, the rate law (7) becomes as:

\[
-\frac{d[\text{CAT}]}{dt} = [\text{CAT}][\text{vitamin}][k_2K_1 + k_4K_3][\text{Brij-35}] \quad \cdots (10)
\]

Further, at high concentrations of vitamin or at lower concentrations of surfactant, the approximation (1+\(K_1[\text{vitamin}]\)) \(\gg\) \(K_3[\text{Brij-35}]\) may be taken and, therefore, the rate law (10) reduces to:

\[
-\frac{d[\text{CAT}]}{dt} = [\text{CAT}][\text{vitamin}][k_2K_1 + k_4K_3][\text{Brij-35}] \quad 1 + K_1[\text{vitamin}] \quad \cdots (11)
\]

The rate laws (10) and (11) are in agreement with the experimental results, i.e. first order, fractional order and zero order dependence of rate with respect to oxidant, substrate and acid, respectively. The rate is proportional to \((k' + k'' [\text{Brij-35}])\) which has also been observed experimentally.
To evaluate the binding constants between chloramine-T and surfactant, the kinetic data have been analysed in terms of pseudo-phase kinetic model for micellar catalysis reported by Menger and Portnoy. According to Menger and Portnoy model the solubilisation/incorporation/association of the reactant (chloramine-T) into the micellar phase is given in Scheme 2,

\[
\begin{align*}
&(\text{CAT})_m & & k_w \rightarrow \text{products} \\
K_o & + D_n & & \rightarrow (\text{CAT})_m & & k_w \rightarrow \text{products}
\end{align*}
\]

Scheme 2

where, \(k_w\) and \(k_m\) are rate constants in aqueous phase and micellar medium, respectively. \(k_w\) is observed rate constant and \(K_o\) (which is same as \(K_f\) in step (iii) of Scheme 1) is the binding constant for association of chloramine-T with surfactant micelle \((D_n)\).

According to above scheme and observed rate law, the observed rate constant \((k_w)\) may be given as:

\[
1/k_w = \frac{k_w + k_m K_o[D_n]}{1 + K_o[D_n]} \quad \ldots (12)
\]

Equation (12) may be rearranged in form of Eq. (13), which has been found to hold good for micelle catalysis in various reactions.

\[
1 (k_w - k_w) = \frac{1}{(k_m - k_w)} + \frac{1}{K_o(k_m - k_w)[D - \text{CMC}]} \quad \ldots (13)
\]

According to Eq.(13), a plot of \(1/(k_w - k_o)\) against \(1/(\text{CMC})\) should be linear with an intercept. The values of \(k_m\) (rate constant in micellar phase) and \(K_o\) (binding constant) may also be evaluated with the help of intercept and slope of the linear plot.

Considering the association/binding of chloramine-T with micelle, the observed kinetic data have been rationalized in terms of Menger and Portnoy’s model. The plots of \(1/(k_w - k_o)\) against \(1/([D] - \text{CMC})\) in case of each vitamin at different temperatures have been found to be linear. The values of \(K_o\) and \(k_m\) have also been evaluated and are given in Table 3.

It is observed that the value of \(k_m\) or \(K_o\) increases on increasing temperature.

Thus, the oxidation of vitamins by chloramine-T in non-ionic micellar medium proceeds via incorporation/association of chloramine-T with surfactant micelle.

Acknowledgement
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References