Acetylcholinesterase: Reversible Inhibitors, Substrate Inhibition*

IRWIN B. WILSON AND J. ALEXANDER

From the Departments of Neurology and Biochemistry, College of Physicians and Surgeons, Columbia University, New York 32, New York

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The behavior of hydrolytic enzymes in general and acetylcholinesterase in particular is best understood by assuming that a labile acyl enzyme is formed as an intermediate during hydrolysis (1-3). For acetylcholinesterase the mechanism is:

\[
\text{Acetylcholine + enzyme} \rightleftharpoons \text{acyl enzyme} + \text{choline}
\]

\[
\text{acyl enzyme} + \text{water} \rightarrow \text{acetic acid} + \text{enzyme}
\]

Observations with acetylcholinesterase can be well explained by postulating that the active site contains two subsites: one, an anionic site which binds and orients substituted ammonium ions, and the other, an esteratic site where the hydrolytic process occurs and which contains a basic group which is acetylated and deacetylated during the process (4, 5).

The formation of an acetyl enzyme suggests some interesting kinetic consequences, especially if the second step is slower or at least not very much more rapid than the first. In this case, simple reversible inhibitors such as substituted ammonium ions may act not only by competition with the substrate for the free enzyme but possibly by combining with the acetyl enzyme at the anionic site. It is easy to imagine that the deacetylation would be sterically blocked, especially if the water molecule had to approach from the direction of the anionic site. This restriction on the direction of the approaching water molecule is to be anticipated for the following reason. The enzyme must catalyze the synthesis of acetylcholine as well as its hydrolysis. In the process of synthesis, a choline molecule attacks the acetyl enzyme and this attack clearly comes from the direction of the anionic site.

If, then, the hydrolysis of the acetyl enzyme can be inhibited by reversible inhibitors, the kinetics should show a noncompetitive component, i.e., a plot of the reciprocal velocity against the reciprocal substrate concentration should intercept the ordinate at a position displaced upward from the intercept obtained in the absence of the inhibitor in accordance with Equation 1 (6):  

\[
\frac{1}{v} = \frac{1}{kE^0} + \frac{1}{K_a} \left[ 1 + \frac{K_m}{K_a} \left( \frac{1 + (S)/K_s}{1 + (S)} \right) \right] \frac{1}{(S)}
\]

(1)

where \(v\) is the initial velocity, \(E^0\) is the total concentration of enzyme and the other quantities are defined by the scheme

\[
E + S \rightleftharpoons \frac{k_1}{k_2} E + S \rightarrow \frac{P_1}{k_4} E'
\]

\[
E' + I \rightleftharpoons E'I, K_I
\]

\[
E' + I \rightleftharpoons E' + I', K_{I'}
\]

\[
K_m = \frac{k_2}{k_1}
\]

\[
k = \frac{k_4k_1}{k_3 + k_4}
\]

Here \(E'\) is the acetyl enzyme, \(P_1\) is choline, \(P_2\) is acetic acid, \(K_I\) and \(K_{I'}\) are dissociation constants and the other symbols have their standard meaning.

It is known that reversible inhibitors, for example tetramethylammonium ion, can prevent the reaction of diethylphosphoryl derivatives of acetylcholinesterase with hydroxylamine and other acetylcholinesterase reactivators (7). Since the hydrolysis of the acetyl enzyme is clearly analogous to this reaction, it is reasonable to expect that it should be inhibited by tetramethylammonium ion. Earlier measurements by a rather approximate method (manometric) with a number of simple quaternary ammonium ions did not indicate any displacement of the \(v^{-1}\) intercept (8).

This seeming inconsistency would be explained if \(k_a/k_s\) were very large. There is evidence, however, although not on a very firm basis, that \(k_s\) is not very different from \(k_a\), possibly \(\frac{1}{2}\) the value of \(k_s\). Also, if this explanation were true we should lose a highly plausible explanation of substrate inhibition. Another possibility is that these inhibitors are very much more poorly bound by the acetyl enzyme than by the free enzyme and therefore only measurements of high precision have any possibility of revealing the \(v^{-1}\) displacement. There is, in fact, some support for this possibility in that these compounds were found to be bound by the diethylphosphonyl enzyme, on the order of 100 times more poorly than by the free enzyme. This explanation for the failure to detect a \(v^{-1}\) displacement with simple quaternary ammonium ions is reasonable, but we need some positive evidence for the correctness of the general theory and for the theory of substrate inhibition upon which it depends. In this theory of substrate inhibition it is postulated that the hydrolysis of the acetyl enzyme is prevented by the binding of a molecule of acetylcholine (9).
Fries (10) has found that some inhibitors, notably cis-2-dimethylaminocyclohexanol, show a noncompetitive component; and this compound has been further investigated by Krupka and Laidler (6) in terms of Equation 1. They have shown that the \( v^{-1} \) displacement is obtained when acetylcholine is the substrate but not when the substrate is methylaminocarbamic acid. Prior information has indicated that \( k_1/k_2 \) was probably rather less than one for acetylcholine and probably rather larger than one for methylaminocarbamic acid (9). This experiment rather strongly suggests the correctness of the theory.

In this paper we report the results of a reinvestigation of the kinetics of inhibition by a precise method. It is shown that the \( v^{-1} \) displacement is quite general. We have included compounds which appear to be especially pertinent to the theory of substrate inhibition.

We also report studies on the inhibition of the hydrolysis of methylcarbamyl enzyme by substituted ammonium ions. The methylcarbamyl enzyme has a more convenient half-life (38 minutes) than the carbamyl enzyme (2 minutes). It would appear that methylcarbamyl enzyme would be an analogue of propionyl enzyme and carbamyl enzyme of acetyl enzyme but the distinction is not important because acetyl enzyme and propionyl enzyme appear to have the same kinetic properties, as judged by the fact that the kinetics of the hydrolysis of acetylcholine and propionylcholine are the same (12). Because of the planar structure of the carbamyl function, this group has a smaller effective volume than an acetyl group and this might be reflected in smaller steric effects.

The hydrolysis of methylcarbamyl enzyme and its inhibition are represented by

\[
E^o + \text{methylcarbamyl enzyme} \rightarrow E + \text{methylcarbamic acid} \quad \text{and} \quad E^o + I \rightarrow E^o-I; K_{I^o}
\]

where the double primes are used to avoid confusion with the acetyl enzyme. The rate of recovery is given in terms of half-times by

\[
t_1 = t_1^o \left[ 1 + \frac{(I)}{K_{I^o}} \right]
\]

**EXPERIMENTAL PROCEDURE**

**Enzyme**—Acetylcholinesterase was prepared from *Electrophorus electricus* by the method of Lawler (13) and had an activity of 0.93 mmole of acetylcholine hydrolyzed per minute (25°C, pH 7.0, 0.1 M NaCl, 0.02 M MgCl₂, 0.005% gelatin and acetylcholine concentration 1 × 10⁻⁴ M) per mg of protein and 3.68 per ml of solution.

**Hydrolysis of Acetylcholine**—The kinetic measurements were made with a Beckman type K automatic titrator modified so that the electrical pulses operate a rotary solenoid coupled to a lead screw which advances the plunger in a 1-ml syringe and thereby delivers aliquots of 0.2 μl of 0.010 M NaOH. Careful "CO₂-free" technique was followed, including a stream of N₂ over the liquid in the reaction vessel.

The reaction was started by the addition of sufficient concentrated acetylcholine solution to make a final concentration of 1 × 10⁻⁴ M or 2 × 10⁻⁴ M. After a few minutes of reaction during which only a few per cent of the substrate was hydrolyzed another portion of acetylcholine solution was added to bring the concentration to a new value. In this way 4 or 5 substrate concentrations were used up to a maximal concentration of 1 × 10⁻³ M. Higher concentrations were not used because of substrate inhibition. Small corrections of 2.5% and less were applied for substrate inhibition and the average value of the concentration was used for plotting the data in accordance with Equation 1. The sum of the percentage deviations from the best straight line divided by the number of points minus 2 were generally well less than 1%.

**Hydrolysis of Methylcarbamyl Enzyme**—The methylcarbamyl enzyme was prepared by incubating methyl carbamylcholine with concentrated enzyme. The recovery was started by diluting the solution 40 times with buffer solution (of the same composition as described above plus 0.02 M sodium phosphate) containing the reversible inhibitor. The free and active enzyme was measured at some twelve time intervals by the Hestrin (14) hydroxamic acid method with assay times of 1 or 2 minutes.

The half-times were determined graphically from linear plots of \( \log(E^o/E^t) \) against time. The precision here was much poorer than in the case of the hydrolysis of acetylcholine, the average deviation from a straight line being of the order of 5%; the half-times had a precision of about 10% and the inaccuracy in \( K_I^o \) probably is about 20%.

The inhibition of the hydrolysis of methylcarbamyl enzyme by acetylcholine was measured in the automatic titrator. In this case acetylcholine had the dual role of also continuously measuring the concentration of active enzyme. In this technique the amount of hydrolysis must be kept to well below 0.1 mm because choline is a reactivator.

**RESULTS**

A displacement of the \( v^{-1} \) intercept was found in all cases. With tetramethylammonium ion, pentytrimethylammonium ion, and phenyltrimethylammonium ion, the displacement was quite small. In other cases it was much more pronounced and with trimethylammonium ion and dimethylammonium ion, it was prominent. The kinetic constants calculated from Equation 1 are presented in Table I and some typical experimental data are shown in Fig. 1. In those cases where \( K_I \) is very much smaller (50 to 100 times) than \( K_I^o (1 + (k_1/k_2)) \) only the order of magnitude of the latter can be determined. It is easy to understand that, in cases like tetramethylammonium ion, the displacement was not previously noted.

The dissociation constants for binding with methylcarbamyl enzyme \( (K_I^o) \) are also given in Table I and some experimental results are shown in Fig. 2. These constants were calculated from Equation 3. In one case, tetramethylammonium ion, the line was distinctly curved. This might be interpreted as indicating that the \( E^o-I \) complex can react with water to some extent. If this should be the correct reason for the curvature, the rate of hydrolysis would come out to be less than 10% of the rate of hydrolysis of \( E^o \). The phenomenon, although not very important for the carbamyl enzyme, raises the question whether the corresponding complex with the acetyl enzyme might not react readily with water, and whether this is the explanation of the small \( v^{-1} \) displacement, rather than poor binding of tetramethylammonium ion with the acetyl enzyme. This possibility was investigated by measuring the displacement with tetramethylammonium ion and dimethylammonium ion together. If tetramethylammonium ion is well bound but does not completely (or nearly completely) prevent deacetylation, the combined displace-
ment should be less than that found with dimethylammonium ion alone. It was found, however, that the combined displacement was the sum of the independent displacements. We can there-

**Table I**

<table>
<thead>
<tr>
<th>No.</th>
<th>Compound</th>
<th>Acetylcholine hydrolysis</th>
<th>Methylarcarbameyl enzyme hydrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$K_I$</td>
<td>$K_I'(1 + \frac{k_4}{k_2})$</td>
</tr>
<tr>
<td>1</td>
<td>$[(\text{CH}_3)_4\text{N}]^+ \text{I}^-$</td>
<td>$1.2 \times 10^{-3}$</td>
<td>$\sim 5 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>(Tetramethylammonium ion)</td>
<td></td>
<td>$2.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>2</td>
<td>$[(\text{CH}_3)_3\text{NH}]^+ \text{Cl}^-$</td>
<td>$4.8 \times 10^{-6}$</td>
<td>$4.0 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>(Trimethylammonium ion)</td>
<td></td>
<td>$4.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>3</td>
<td>$[(\text{CH}_3)_2\text{NH}_2]^+ \text{Cl}^-$</td>
<td>$2.6 \times 10^{-2}$</td>
<td>$3.2 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>(Dimethylammonium ion)</td>
<td></td>
<td>$3.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>4</td>
<td>$[(\text{CH}_3)_2\text{H}_2\text{N}]^+ \text{I}^-$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$\sim 2 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>(Pentyltrimethylammonium ion)</td>
<td></td>
<td>$1.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>5</td>
<td>$[(\text{CH}_3)_2\text{N}-\text{CH}_2\text{COOH}_2\text{H}_3]^+ \text{Br}^-$</td>
<td>$2.0 \times 10^{-3}$</td>
<td>$2.0 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>($\beta$-Trimethylaminopropionic acid ethyl ester)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$[(\text{CH}_3)_2\text{N}-\text{CH}_2\text{COOCCH}_3]^+ \text{Br}^-$</td>
<td>$7.7 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>($\gamma$-Trimethylaminobutyric acid ethyl ester)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$[(\text{CH}_3)_2\text{N}-\text{CH}_2\text{OCOCH}_3]^+ \text{Br}^-$</td>
<td>$1.4 \times 10^{-4}$</td>
<td>$3.2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>(Acetylcholine)</td>
<td></td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>8</td>
<td>$\text{N}^+\text{CH}_3 \text{I}^-$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>($N$-Methylpyridinium ion)</td>
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<td>$1.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>9</td>
<td>$\text{N}^+\text{CH}_3 \text{I}^-$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$\sim 2 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>(Phenyltrimethylammonium ion)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* It appears that $k_4 < k_3$ so that this expression approximates $K_I'$.

† $K_m$ value, $K_m = \frac{k_2 + k_3}{k_1} / (1 + (1 + k_2) / k_2)$; see Equation 1.

‡ $K_I'(1 + \frac{k_4}{k_2})$; see Equation 2.

**Fig. 1.** Lineweaver-Burk plots of the kinetics of the hydrolysis of acetylcholine in the presence of three representative inhibitors and by itself. The displacement of the ordinate intercept indicates a noncompetitive component in the inhibition.

**Fig. 2.** The half-time for the recovery of the methylcarbamyl derivative of acetylcholinesterase by reaction with water in the presence of various concentrations of two reversible inhibitors and acetylcholine. All inhibit the reaction with water.

We conclude that the tetramethylammonium ion-acetyl enzyme complex does not react readily with water.

**DISCUSSION**

It is helpful to consider first the data for the two smallest inhibitors, dimethylammonium ion and trimethylammonium ion. The dissociation constants for binding with the free enzyme are about the same as for binding with the methylcarbamyl enzyme and are also about the same as the combination $K_I'(1 + (k_4/k_2))$. There is certainly no reason to suppose that binding to the acetyl enzyme would be stronger. We may therefore conclude that $k_4$ is rather smaller than $k_2$ and that $K_I'(1 + k_4/k_2)$ approximates $K_I'$. Then we have the reassuring result that
binding with the enzyme and with its two derivatives has about the same strength. Previous observations on the temperature dependence of the rate of enzymic hydrolysis of acetylcholine had also suggested that $k_4$ was smaller than $k_b$, possibly $\frac{1}{4}$ the value (9).

It is interesting that the affinity of tetramethylammonium ion for the free enzyme is about four times greater than that of trimethylammonium ion. In earlier work, the $I_{50}$ values when $\langle S \rangle = 4 \times 10^{-3}$ M were found to be about the same. The present measurements of the dissociation constants clear up a minor discrepancy which was recognized after the earlier $I_{50}$ values were published. It had been concluded that the fourth methyl group in tetramethylammonium ion projected into the solution and was without binding properties. This physical picture is what one would, a priori, assume and hardly needed much confirmation. Upon reflection, however, it is clear that the nonbinding methyl group can be selected in four ways and that tetramethylammonium ion ought, therefore, to be about four times better bound than trimethylammonium ion. (A more detailed analysis does not seem justified.)

We now consider the theory of substrate inhibition. From the fact that the hydrolysis of the carbamyl enzyme can be inhibited by reversible inhibitors, it is clear that the hydrolysis of the acetyl enzyme should also be inhibited. This is substantiated by the $v^{-1}$ displacement as already discussed. The only questions remaining are, "can acetylcholine inhibit the hydrolysis of the acetyl enzyme, and if so, can it do so at concentrations where substrate inhibition occurs?"

Studies with the carbamyl enzyme showed that acetylcholine could prevent its hydrolysis and yielded a dissociation constant of $2 \times 10^{-2}$ M. This is very nearly the same as the dissociation constant obtained for binding with the acetyl enzyme when that constant is evaluated in terms of Equation 2. Moreover, it is right in line with the dissociation constants for the binding of the acetyl enzyme with the reverse esters, compounds No. 5 and 6 (Table I), which bear an obvious relationship to acetylcholine but are not substrates. These results leave little doubt that the correct explanation of substrate inhibition is that the decylation of the acetyl enzyme is prevented by the binding of a molecule of acetylcholine.

**SUMMARY**

Kinetic measurements of relatively high precision show that reversible inhibitors of acetylcholinesterase have a noncompetitive component. These findings are consistent with deductions arising from the intermediate formation of an acetyl enzyme in enzymic hydrolysis, for it follows that it should be possible to inhibit the deacylation and this introduces the noncompetitive component. In support of this theory, reversible inhibitors are shown to inhibit the hydrolysis of methylcarbamyl enzymes, a reaction analogous to the hydrolysis of the acetyl enzyme. It is shown that acetylcholine inhibits the hydrolysis of the methylcarbamyl enzyme and, therefore, would be expected to inhibit the hydrolysis of the acetyl enzyme. This would produce substrate inhibition. The binding constant of acetylcholine with the acetyl enzyme is nearly the same as with the carbamyl enzyme.

**REFERENCES**

Acetylcholinesterase: Reversible Inhibitors, Substrate Inhibition
Irwin B. Wilson and J. Alexander