

# CARBONIC ANHYDRASE: KINETICS OF REMOVAL OF Zn(II) By 2,6-PYRIDINECARBOXYLATE

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## Abstract

In the past decade, supervised activity recognition methods have been studied by many researchers, however these methods still face many challenges in real world settings. Supervised activity recognition methods assume that we are provided with labeled training examples from a set of predefined activities. Annotating and hand labeling data is a very time consuming and laborious task. Also, the assumption of consistent pre-defined activities might not hold in reality. More importantly, these algorithms do not take into account the streaming nature of data, or the possibility that the patterns might change over time. In this chapter, we will provide an overview of the state of the art *unsupervised* methods for activity recognition. In particular, we will describe a scalable activity discovery and recognition method for complex large real world datasets, based on sequential data mining and stream data mining methods.

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# Introduction

Carbonic anhydrase (CA) catalyzes the interconversion of carbon dioxide and carbonic acid/bicarbonate as follows:



As shown in figure 1, the CA active site contains a  $\text{Zn}^{2+}$  cofactor (denoted as  $\text{CA}\cdot\text{Zn}$ ), which it relies upon for its catalytic activity. The zinc ion can be stripped from the enzyme using a Lewis base ligand, which donates electrons to the ion to form a covalent bond. The ligand being studied in this experiment is 2,6-pyridinecarboxylate, commonly called dipicolinate (or dipic). Figure 2 shows the structure of dipic. In this experiment, the rate of zinc removal by dipic will be measured.

## Mechanism

When  $[\text{dipic}] \gg [\text{CA}]$ , that is, when  $\frac{[\text{dipic}]}{[\text{CA}]} \geq 25$ , then the removal of zinc is pseudo-first-order with respect to  $\text{CA}\cdot\text{Zn}$  because the concentration of dipic, denoted as L, does not change appreciably. Thus the formation of the inactive enzyme, apoCA, can be modeled using the following rate equation:

$$\frac{d[\text{apoCA}]}{dt} = k_{obs}[\text{CA}\cdot\text{Zn}] \quad (2)$$

The pseudo-first-order rate constant,  $k_{obs}$ , increases as  $[\text{L}]$  increases, but levels off at sufficiently high concentrations of L. Biochemists will recognize behavior similar to Michaelis-Menten enzyme kinetics in which the enzyme,  $\text{CA}\cdot\text{Zn}$ , and the substrate, L, reversibly form a  $\text{CA}\cdot\text{Zn}\cdot\text{L}$  complex with association constant  $K_{EML}$  (EML stands for Enzyme-Metal-Ligand):



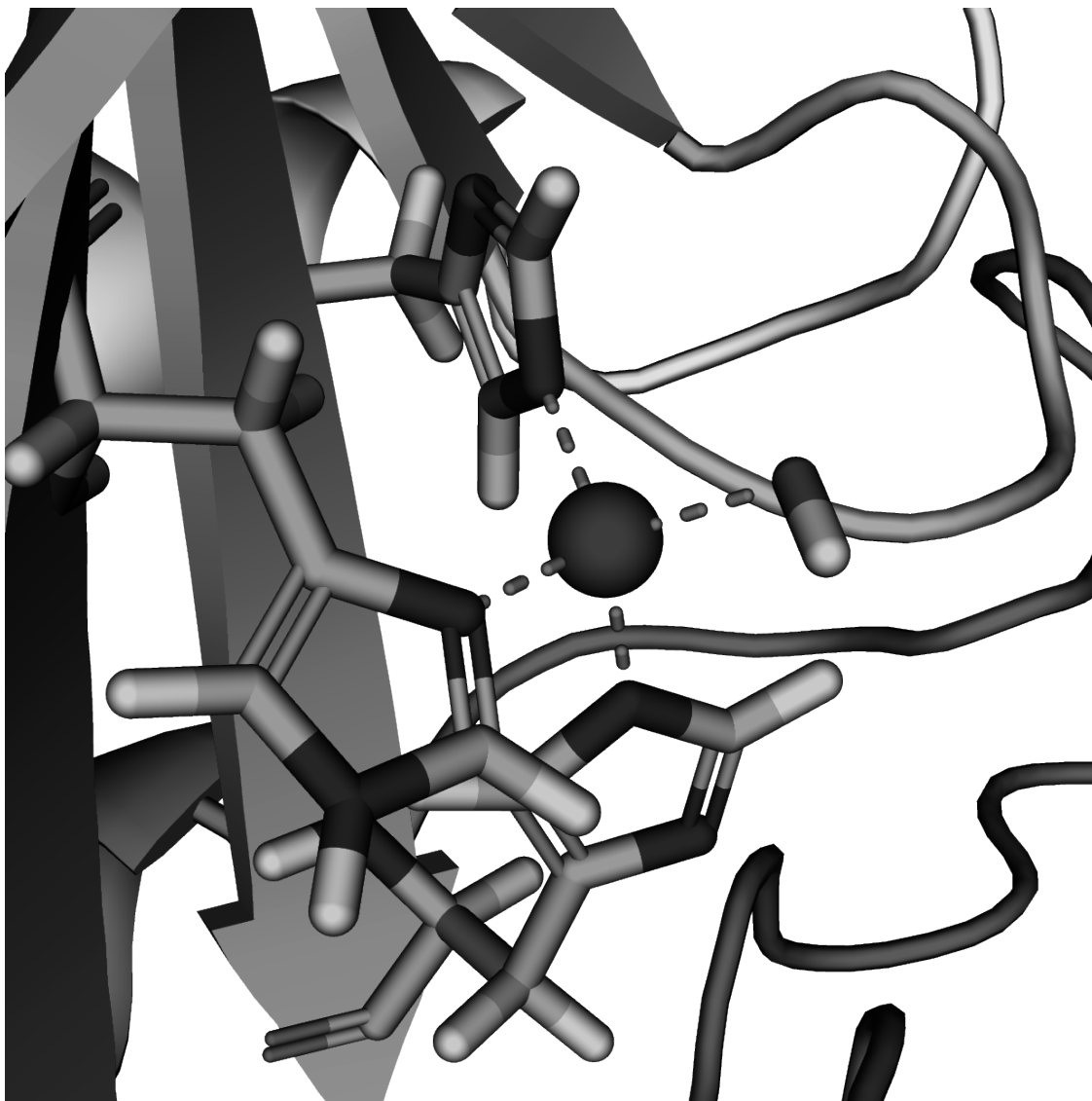


Figure 1:  $\text{Zn}^{2+}$  cofactor in the active site of human carbonic anhydrase II<sup>1</sup>

This can be modeled as follows:

$$K_{EML} = \frac{[\text{CA} \cdot \text{Zn} \cdot \text{L}]}{[\text{CA} \cdot \text{Zn}][\text{L}]} \quad (4)$$

$\text{CA} \cdot \text{Zn} \cdot \text{L}$  can either revert back to the original species or irreversibly convert to the inactive form of the enzyme, apoCA, and the covalently bound zinc-dipic molecule, ZnL:



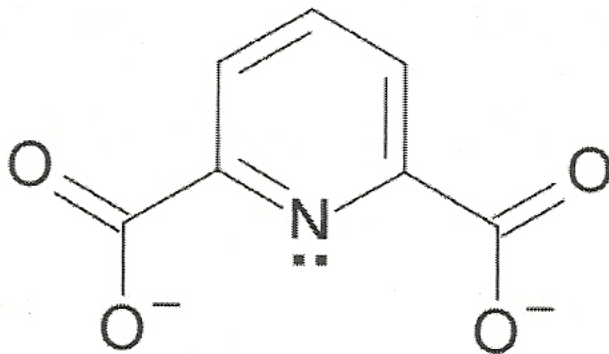


Figure 2: Structure of 2,6-pyridinedicarboxylate (dipic)<sup>2</sup>

This yields the following differential rate law:

$$\frac{d[\text{apoCA}]}{dt} = k_d[\text{CA}\cdot\text{Zn}\cdot\text{L}] \quad (6)$$

Note the difference in assumptions between this reaction and the Michaelis-Menten model; M-M kinetics assumes the enzyme is reformed and that only the substrate is modified, while (5) shows that both the substrate and the enzyme are permanently modified. Recall that  $[\text{L}] \gg [\text{CA}\cdot\text{Zn}]$ , so  $[\text{L}]$  can be treated as a constant,  $[\text{L}]_0$ , which is substituted into a rearranged form of equation (4),

$$[\text{CA}\cdot\text{Zn}\cdot\text{L}] = K_{EM\text{L}}[\text{CA}\cdot\text{Zn}][\text{L}]_0 \quad (7)$$

Carbonic anhydrase can exist in one of three forms: the metalloenzyme  $\text{CA}\cdot\text{Zn}$ , the enzyme-metal-ligand complex  $\text{CA}\cdot\text{Zn}\cdot\text{L}$ , or the inactivated enzyme apoCA. Initially, all CA is tied up in the metalloenzyme, and none exists as  $\text{CA}\cdot\text{Zn}\cdot\text{L}$  or apoCA. As the activated form of the enzyme gets bound to L and then inactivated,

$$[\text{CA}\cdot\text{Zn}] = [\text{CA}\cdot\text{Zn}]_0 - [\text{apoCA}] - [\text{CA}\cdot\text{Zn}\cdot\text{L}], \quad (8)$$

which can be combined with equation (7) to yield

$$[\text{CA}\cdot\text{Zn}] = [\text{CA}\cdot\text{Zn}]_0 - [\text{apoCA}] - K_{EML}[\text{CA}\cdot\text{Zn}][\text{L}]_0 \quad (9)$$

and can be rearranged as follows:

$$[\text{CA}\cdot\text{Zn}] = \frac{[\text{CA}\cdot\text{Zn}]_0 - [\text{apoCA}]}{1 + K_{EML}[\text{L}]_0} \quad (10)$$

Equations (6) and (7) can be combined to give

$$\frac{d[\text{apoCA}]}{dt} = k_d K_{EML}[\text{CA}\cdot\text{Zn}][\text{L}]_0 \quad (11)$$

Therefore, the rate of apoCA formation is first-order with respect to CA·Zn. Combining equations (11) and (10) yields

$$\frac{d[\text{apoCA}]}{dt} = k_d K_{EML}[\text{L}]_0 \frac{[\text{CA}\cdot\text{Zn}]_0 - [\text{apoCA}]}{1 + K_{EML}[\text{L}]_0} \quad (12)$$

Rearranging and integrating,

$$\begin{aligned} \int_{[\text{apoCA}]_0}^{[\text{apoCA}]_t} \frac{d[\text{apoCA}]}{[\text{CA}\cdot\text{Zn}]_0 - [\text{apoCA}]_t} &= \int_0^t \frac{k_d K_{EML}[\text{L}]_0}{1 + K_{EML}[\text{L}]_0} dt \\ &= \frac{k_d K_{EML}[\text{L}]_0}{1 + K_{EML}[\text{L}]_0} t \end{aligned} \quad (13)$$

The left side must be integrated using u-substitution:

$$u = [\text{CA}\cdot\text{Zn}]_0 - [\text{apoCA}]_t$$

$$du = -d[\text{apoCA}]$$

To change the integral boundaries,

$$u(t = 0) = [\text{CA} \cdot \text{Zn}]_0, \text{ since no inactivated enzyme has been formed}$$

$$u(t = t) = [\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t$$

Therefore,

$$\begin{aligned} \int_{[\text{apoCA}]_0}^{[\text{apoCA}]_t} \frac{d[\text{apoCA}]}{[\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t} &= - \int_{[\text{CA} \cdot \text{Zn}]_0}^{[\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t} \frac{du}{u} \\ &= -\ln(u) \Big|_{[\text{CA} \cdot \text{Zn}]_0}^{[\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t} \\ &= -\ln \left( \frac{[\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t}{[\text{CA} \cdot \text{Zn}]_0} \right) \end{aligned} \quad (14)$$

Combining the evaluated integrals from equations (14) and (13) yields

$$\ln \left( \frac{[\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t}{[\text{CA} \cdot \text{Zn}]_0} \right) = - \frac{k_d K_{EML} [\text{L}]_0}{1 + K_{EML} [\text{L}]_0} t \quad (15)$$

Assuming steady-state conditions for  $\text{CA} \cdot \text{Zn} \cdot \text{L}$  - that is,  $[\text{CA} \cdot \text{Zn} \cdot \text{L}]$  is always negligible - then  $\frac{[\text{CA} \cdot \text{Zn}]_0 - [\text{apoCA}]_t}{[\text{CA} \cdot \text{Zn}]_0}$  is simply the fraction of  $\text{CA} \cdot \text{Zn}$  remaining after reaction time  $t$  and can be referred to as  $F_{\text{CA} \cdot \text{Zn}}$ :

$$\ln(F_{\text{CA} \cdot \text{Zn}}) = - \frac{k_d K_{EML} [\text{L}]_0}{1 + K_{EML} [\text{L}]_0} t \quad (16)$$

Since  $-\frac{k_d K_{EML} [\text{L}]_0}{1 + K_{EML} [\text{L}]_0}$  is a constant for a given concentration of dipic, equation (16) exhibits linear behavior while the solution contains active enzyme. Therefore, a linear least squares regression procedure can be performed for measurements of  $\ln(F_{\text{CA} \cdot \text{Zn}})$  over time (until those measurements level off, which indicates that all the enzyme is used up), and the slope, denoted  $-k_{obs}$ , will be

$$-k_{obs} = - \frac{k_d K_{EML} [\text{L}]_0}{1 + K_{EML} [\text{L}]_0} \quad (17)$$

Taking the reciprocal of equation (17) yields

$$\begin{aligned}
\frac{1}{k_{obs}} &= \frac{1 + K_{EML}[L]_0}{k_d K_{EML}[L]_0} \\
&= \frac{1}{k_d K_{EML}[L]_0} + \frac{K_{EML}[L]_0}{k_d K_{EML}[L]_0} \\
&= \frac{1}{k_d K_{EML}} \times \frac{1}{[L]_0} + \frac{1}{k_d}
\end{aligned} \tag{18}$$

Again, a linear pattern is observed; measuring  $k_{obs}$  at several different dipic concentrations enables one to perform a least squares regression procedure on  $\frac{1}{k_{obs}}$  versus  $\frac{1}{[L]_0}$  to determine the slope,  $m = \frac{1}{k_d K_{EML}}$ , and intercept,  $b = \frac{1}{k_d}$ .  $k_d$  and  $K_{EML}$  are thus calculated as follows:

$$k_d = \frac{1}{b} \tag{19}$$

$$K_{EML} = \frac{b}{m} \tag{20}$$

## Rate Measurements

While equations (16) and (17) seem to imply that the determination of  $k_{obs}$  requires knowing  $[CA \cdot Zn]$  or  $[apoCA]$  at any point in time, in reality a plot of  $f(t)$  vs  $t$ , where  $f(t)$  is proportional to  $F_{CA \cdot Zn}$ , will still exhibit the same slope  $-k_{obs}$ . The Michaelis-Menten kinetics model states that, for sufficiently large substrate concentrations, the enzyme is fully saturated and the reaction velocity asymptotically approaches a number,  $V_{max} = k_{cat}[CA \cdot Zn]$ , where  $k_{cat}$  (the “turnover number”) is amount of substrate that can be converted to product by a single saturated enzyme molecule in a given unit of time.<sup>3</sup> Thus for sufficiently large concentrations of substrate, the enzyme catalytic activity fulfills the requirement of proportionality to  $F_{CA \cdot Zn}$ . Ideally, the determination of the enzymatic activity from  $V_{max}$ , that is, an enzyme assay, can be done using a substrate which is cheap, readily available, and easily measurable. As Figure 3 shows, carbonic anhydrase happens to hydrolyze para-nitrophenyl acetate (pNPA) to form para-nitrophenol and acetic acid:

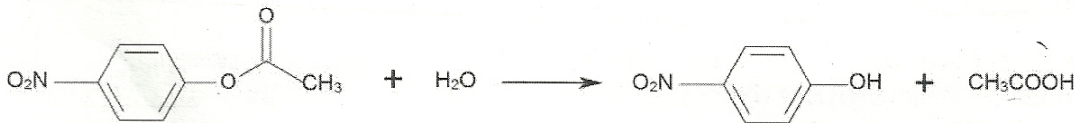


Figure 3: Carbonic anhydrase-catalyzed hydrolysis of para-nitrophenyl acetate (pNPA) to para-nitrophenol and acetic acid<sup>2</sup>

Para-nitrophenol absorbs strongly at 348nm. Recall that Beer's law states

$$A = \epsilon bc \quad (21)$$

where  $A$  is the measured absorbance at a particular wavelength,  $\epsilon$  is the molar absorptivity,  $b$  is the measurement path length, and  $c$  is the concentration.<sup>4</sup> Since  $b$  and  $\epsilon$  stay constant,  $A$  is dependent only on  $c$ .  $c$  varies with time, therefore  $\left(\frac{dA}{dt}\right)_{cat}$  is proportional to the change in para-nitrophenol (that is, the reaction velocity). Because the reaction occurs to a nontrivial extent without enzyme catalysis, a baseline correction is needed,  $\left(\frac{dA}{dt}\right)_{uncat}$ , which can be obtained either from a solution containing only pNPA or a mixture of pNPA and apoCA (that is, after sufficient time has passed to inactivated all carbonic anhydrase before taking the assay). In this experiment,  $\left(\frac{dA}{dt}\right)_{uncat}$  was determined from the solution of pNPA with no enzyme added. Thus, equation (16) can be implemented using

$$\ln \left( \frac{dA}{dt} \right)_{cat} = \ln \left( \frac{\left( \frac{dA}{dt} \right)_t}{\left( \frac{dA}{dt} \right)_{uncat}} \right) \quad (22)$$

(note: this also fulfills the logarithm function's unitless requirement.)



## Procedure

This experiment was performed using a Spectral Instruments model SI 440 spectrophotometer, which includes a CCD detector and fiber optic probe. The spectrophotometer was set to detect absorbance at wavelength 348 nm every five seconds over the course of two minutes. Device precision was set to “low,” and a blank was obtained and locked. A sample of deionized water was measured to ensure absorbance stayed constant, preventing systematic errors from faulty instrumentation.

A 0.003 M aqueous pNPA solution was prepared by dissolving 25 mg solid pNPA in 1.5 mL acetone within a 250 mL Erlenmeyer flask, then slowly adding 50 mL deionized water while stirring vigorously to prevent precipitation. Assays were constructed by combining 1.7 mL deionized water, 0.3 mL HEPES buffer (0.25 M, pH 8.0), and 1.0 mL pNPA solution. To measure the uncatalyzed assay velocity  $\left(\frac{dA}{dt}\right)_{uncat}$ , 40  $\mu$ L deionized water was added to an assay containing no dipic, and the absorbance was measured for two minutes.

Five dipic concentrations were tested: 0.20 M, 0.10 M, 0.05 M, 0.032 M, and 0.016 M. For each [dipic], a 500  $\mu$ L solution was prepared consisting of 250  $\mu$ L aqueous bovine carbonic anhydrase ( $10^{-4}$  M in 0.125 M phosphate buffer, pH 7.5) and the required volumes of phosphate buffer (0.125 M, pH 7.4) and dipic (0.4 M in 0.125 M phosphate buffer, pH 7.4) needed to dilute to the specified [dipic]. In each run, the carbonic anhydrase and buffer were mixed and placed in a 25°C water bath to equilibrate for several minutes. Dipic was mixed just prior to starting measurements. After one minute, and then again at regular intervals over the course of one hour (or until  $\frac{dA}{dt}$  measurements stopped decreasing, signifying full holoenzyme depletion), a 40  $\mu$ L aliquot of CA/dipic solution was transferred to an assay cuvette, and a two-minute  $\frac{dA}{dt}$  measurement was recorded.

## Sample Calculations

As Equation (22) demonstrates, a baseline correction is needed to convert the raw absorbance velocity,  $\left(\frac{dA}{dt}\right)_t$ , to a proportion which can take the place of  $F_{CA \cdot Zn}$  in Equation (16).  $\left(\frac{dA}{dt}\right)_{uncat}$  was found to be  $3.18 \times 10^{-5} \text{ sec}^{-1}$ . One data point that was measured for the 0.10 M dipic concentration experiment was  $\left(\frac{dA}{dt}\right)_{t=1.08 \text{ min}} = 0.00295 \text{ sec}^{-1}$ . Therefore, **(note: consider changing t in prior equation to be less ambiguous)**

$$\begin{aligned} \ln \left( \frac{dA}{dt} \right)_{cat} &= \ln \left( \frac{\left(\frac{dA}{dt}\right)_t}{\left(\frac{dA}{dt}\right)_{uncat}} \right) \\ &= \ln \left( \frac{0.00295 \text{ sec}^{-1}}{3.18 \times 10^{-5} \text{ sec}^{-1}} \right) \\ &= 4.530 \end{aligned}$$

Recall from Equation (16) that  $-k_{obs}$  is the slope obtained from a least-squares regression of multiple assay  $\ln \left(\frac{dA}{dt}\right)_{cat}$  readings versus CA/dipic reaction time. For 0.10 M dipic, this was found to be  $-k_{obs} = -0.090 \text{ min}^{-1}$  (so  $k_{obs} = 0.090 \text{ min}^{-1}$ ).

Equation (18) implies that a least-squares regression of  $\frac{1}{k_{obs}}$  versus  $\frac{1}{[L]_0}$  gives a slope,  $m = \frac{1}{k_d K_{EML}}$ , and intercept,  $b = \frac{1}{k_d}$ , which can be used to calculate  $k_d$  and  $K_{EML}$  for the dipic/CA reaction. Empirically,  $m$  was found to have a value of  $0.5372 \text{ M} \cdot \text{mins}$  ( $0.50 \text{ M} \cdot \text{mins}$  rounded to accepted precision from error analysis), and  $b$  was found to be  $8.513 \text{ mins}$  ( $9.0 \text{ mins}$  rounded to accepted precision from error analysis). Thus,

$$\begin{aligned} K_{EML} &= \left( \frac{b}{m} \right) M^{-1} \\ &= \frac{(9.0 \text{ mins})}{(0.5 \text{ M} \cdot \text{mins})} \\ &= 20 \text{ M}^{-1} \end{aligned} \tag{23}$$

$$\begin{aligned}
k_d &= \left(\frac{1}{b}\right) \text{ mins}^{-1} \\
&= \frac{1}{(9.0 \text{ mins})} \\
&= 0.1 \text{ mins}^{-1}
\end{aligned}
\tag{24}$$

## Error Analysis

To determine  $k_{obs}$ , readings of  $\ln \left( \frac{dA}{dt} \right)_{cat}$  were plotted against CA/dipic reaction time, and a least squares regression was performed. From the analysis of 0.10 M dipic,  $m = -0.0936 \text{ mins}^{-1}$  and  $s_m = 0.0207 \text{ mins}^{-1}$ . There were 5 data points taken while active CA enzyme activity was detected, so 3 degrees of freedom were used for the 95% confidence t-factor,  $t_{95} = 3.182$ . From this, a 95% confidence interval was calculated:

$$\begin{aligned} -k_{obs} &= \left( -0.0936 \pm \frac{0.0207 \times 3.182}{\sqrt{5}} \right) \text{ mins}^{-1} \\ &= (-0.090 \pm 0.029) \text{ mins}^{-1} \end{aligned}$$

To calculate  $k_d$  and  $K_{EML}$ , values of  $\frac{1}{k_{obs}}$  retrieved from all five experiments were plotted against  $\frac{1}{[L]_0}$ . A least squares regression determined  $m = 0.5372 \text{ mins} \cdot M$ ,  $s_m = 0.1675 \text{ mins} \cdot M$ ,  $b = 8.513 \text{ mins}$ , and  $s_b = 5.507 \text{ mins}$ . Since 5 runs were performed, there were 3 degrees of freedom. The 95% confidence t-factor was  $t_{95} = 3.182$ . Therefore,

$$\begin{aligned} m_{95} &= \left( 0.5372 \pm \frac{0.1675 \times 3.182}{\sqrt{5}} \right) \text{ mins} \cdot M \\ &= (0.50 \pm 0.24) \text{ mins} \cdot M \end{aligned} \tag{25}$$

$$\begin{aligned} b_{95} &= \left( 8.513 \pm \frac{5.507 \times 3.182}{\sqrt{5}} \right) \text{ mins} \\ &= (9 \pm 8) \text{ mins} \end{aligned} \tag{26}$$

Equation (20) shows how to calculate  $K_{EML}$  from the slope and intercept determined by Equations (25) and (26):

$$K_{EML} = \left( \frac{b}{m} \pm \lambda_{K_{EML}} \right) M^{-1}$$

Therefore, a 95% confidence interval can be established as follows:

$$\begin{aligned}
\lambda_{K_{EML}} &= \sqrt{\left(\frac{\partial K_{EML}}{\partial m}\right)^2 \lambda_m^2 + \left(\frac{\partial K_{EML}}{\partial b}\right)^2 \lambda_b^2} \\
&= \sqrt{\left(-\frac{b}{m^2}\right)^2 \lambda_m^2 + \left(\frac{1}{m}\right)^2 \lambda_b^2} \\
&= \sqrt{\left(-\frac{(9.0 \text{ mins})}{(0.5 \text{ M} \cdot \text{mins})^2}\right)^2 \times (0.24 \text{ M} \cdot \text{mins})^2 + \left(\frac{1}{(0.5 \text{ M} \cdot \text{mins})}\right)^2 \times (8.0 \text{ mins})^2} \\
&= 18 \text{ M}^{-1}
\end{aligned} \tag{27}$$

To calculate  $k_d$ , use the y-intercept of the line passing through a plot of  $\frac{1}{k_{obs}}$  versus  $\frac{1}{[L]_0}$  as determined by Equation (26). From Equation (19),

$$k_d = \left(\frac{1}{b} \pm \lambda_{k_d}\right) \text{ mins}^{-1}$$

These can be combined to give a 95% confidence interval:

$$\begin{aligned}
\lambda_{k_d} &= \sqrt{\left(\frac{\partial k_d}{\partial b}\right)^2 \lambda_b^2} \\
&= \sqrt{\left(-\frac{1}{b^2}\right)^2 \lambda_b^2} \\
&= \sqrt{\left(-\frac{1}{(9.0)^2}\right)^2 \times (8.0)^2} \\
&= 0.10 \text{ mins}^{-1}
\end{aligned} \tag{28}$$

## Data and Results

Five experiments were performed using a constant amount of carbonic anhydrase and varying concentrations of dipic. For each experiment, several measurements of CA-catalyzed pNPA hydrolysis velocities,  $\ln\left(\frac{dA}{dt}\right)_{cat}$ , were taken using spectrophotometry and plotted against the CA/dipic reaction time. The results of these experiments are shown in Figure 4.

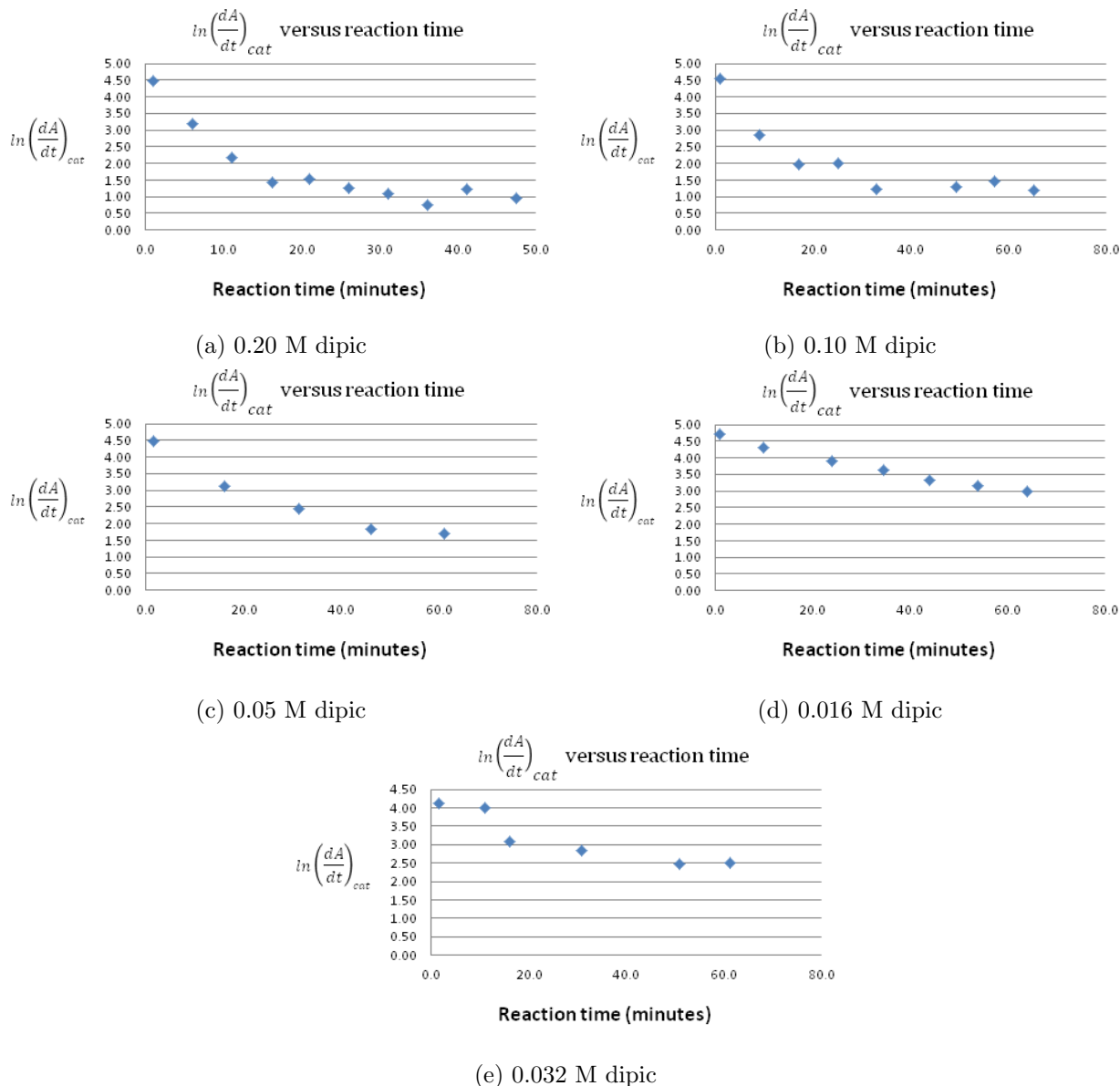


Figure 4:  $\ln\left(\frac{dA}{dt}\right)_{cat}$  measurements versus CA/dipic reaction time for various concentrations of dipic. Slopes of the descending portions of these plots were used to assign values for  $k_{obs}$ .

From the descending portions of the plots shown in Figure 4, five values of  $k_{obs}$  were calculated using the slopes determined by least squares regression. The reciprocals of  $k_{obs}$  and  $[L]_0$  (dipic concentration) were plotted against each other, as shown in Figure 5.

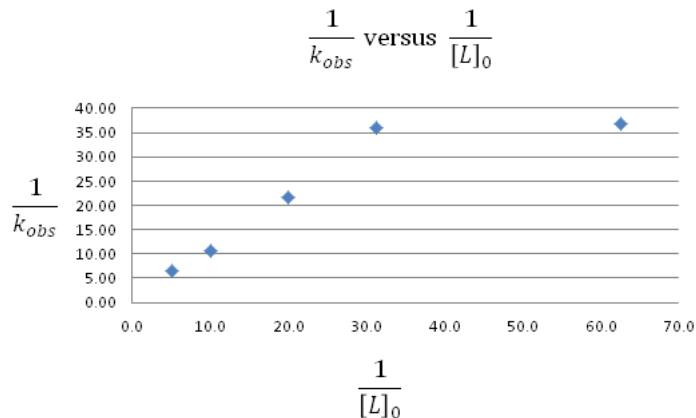


Figure 5: Plot of  $\frac{1}{k_{obs}}$  versus  $\frac{1}{[L]_0}$ . The slope and intercept from this plot were determined by least squares regression and used to calculate  $K_{EML}$  and  $k_d$ , demonstrated by Equations (23) and (24) respectively.

A least squares regression procedure was performed on the data shown in Figure 5 to retrieve values for the slope and intercept of the line passing through those points. Equations (23) and (24) show how these were used to calculate  $K_{EML}$  and  $k_d$ . Table 1 lists these values and their 95% confidence intervals, as well as accepted values reported in literature.

Table 1: Values of  $K_{EML}$  and  $k_d$ , as determined in this experiment as well as accepted values from literature

Constant	Empirical Value	Accepted Value
$K_{EML}$	$(20 \pm 18) M^{-1}$	foobar
$k_d$	$(0.10 \pm 0.10) mins^{-1}$	blah

## References

- (1) RCSB Protein Data Bank. Refined structure of human carbonic anhydrase II at 2.0 Å resolution. <http://www.rcsb.org/pdb/explore/explore.do?structureId=1CA2> (accessed Jun 16, 2014).
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